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Bachelor in Aerospace Engineering
2017/2018

Bachelor Thesis

Logistics analysis of a in-situ resource utilisation mission to the Moon

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July 2018

Abstract

Space exploration has reached a development stage whose main objective is to closely investigate and analyze celestial bodies. Due to its proximity to the Earth, the Moon is an evident starting point for this analysis.

The Moon presents an entirely different environment from that found on Earth, and is extremely hostile to human beings. The absence of an atmosphere causes critical conditions, such as absence of oxygen, vacuum, widely-varying temperatures and severe solar radiation.

However, the lunar surface presents an opportunity to solve some of these issues. The lunar regolith (moon-dust) contains hydrogen, ice-water and other elements that may be employed by alternative methods to create a habitable environment.

In this context, the scope of this research is to analyze the feasibility of fulfilling a long-term mission on the Moon using exclusively local resources, with no dependency on the Earth. This study considers only currently-available ISRU technology, with the purpose of verifying if improvements to existing technology are required to complete a mission of these characteristics.

Keywords

Moon, Lunar regolith, ISRU, Resources, Payload, and Space mission.

Acknowledgment

I would like to dedicate a space of this thesis to all those people who have made possible the realization of this work. Also, to all those who have allowed me to access the necessary information to go ahead with my study, in particular: Manuel Sanjurjo Rivo (Tutor), Nuria Labeaga Martínez, and Javier García-Heras Carretero. At all times they have shown patience, interest and availability.

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1 Introduction

Space exploration began in the mid-twentieth century purely for political reasons. The Cold War launched a space race which culminated with the arrival of man to the Moon. The space race ended as the conflict between both world powers drew to a close.

However, space exploration continues to develop scientifically by launching robotic space probes that are able to perform experiments without the need of bringing humans into space.

These explorations contribute very positively in the economic activity of part-taking countries in terms of scientific innovation, involving scientists, engineers and doctors. Moreover, citizens also benefit from the technology that has been developed though space exploration. Examples of this are the technology to miniaturize components for space missions which is now used in mobile communications; available weather data due to the deployment of meteorological satellites; or web mapping services that function with GNSS technology developed by the space sector. These examples are considered normal in our daily lives, but they are the result of high-technology research for space purposes. Thus, the need for the continuity of space exploration is evident.

Currently, space exploration is in a stage in which the main objective is to closely investigate and analyze celestial bodies, starting with the closest ones, the Moon and Mars. In fact, one of the most discussed ideas is to bring colonies and research bases directly into these environments, creating an in-situ settlement that would accelerate and improve research on these planets. However, as the costs of establishing these settlements on Mars is high due to its distance from Earth, initial trials could be performed on the Moon, which is more achievable due its proximity.

However, facing the hostile conditions of habitability of the Moon for humans is the major barrier for a long-term settlement on the lunar surface. Therefore, it is necessary to firstly identify the possible difficulties that the lunar environment may present, which are caused by the absence of atmosphere.

There are several elements that are essential to the survival on the Moon, namely water, food, oxygen and shelter. If these requirements can be fulfilled using resources found on the Moon, the idea of creating a lunar base may become a reality.

To this end, this thesis analyzes existing technologies that may take advantage of the lunar resources to produce these requirements. Its performance and progress is studied to evaluate the different options that are currently available.

To see its applicability to a plausible scenario, we design a mission to define the quantities and parameters needed for a 6-month expedition to the Moon. The best equipment is selected and measured in term of mass and volume to compute the number of launches required for the mission. In order to evaluate the result, this mission is compared to the alternative of bringing all resources from Earth. After simulating both scenarios, the results indicate the feasibility of this approach.

The main objective of this thesis is to analyze whether the in-situ utilization of lunar resources with current technology is a viable option and if it should be considered as the baseline approach in the near future.

2 Lunar Environment

Before analyzing the different available ISRU technologies, it is of interest to have an overview of the Moon environment. Studying the lunar geology, the different available resources can be reviewed in order to see how they can be used and benefited from them. It will also be seen the different difficulties and possible obstacles that the harsh lunar environment may present.

The Moon geological surface can be categorized in two main areas [1]:

- **Lunar highlands**: It is the ancient, light-colored part of the Moon. It represents the original crust of the Moon and it is composed of basically anorthositic rocks and contain more than 90 % by mass plagioclase in the form of small quantities of magnesium and calcium-based anorthite.
- **Lunar mare**: The darker part of the Moon. It is composed by basaltic lava flow which contains ilmenite among others.

The south polar highlands is an area that provides almost permanent sunlight throughout the year, which is favorable for both illumination and generation of power.

The lunar surface is covered by the so-called Regolith. Regolith is the general term used to designate the layer of unconsolidated, altered materials, such as rock fragments, mineral grains and all other surface deposits, which rests on unchanged solid rock. The physical properties of the lunar surface are basically the result of the mechanical disintegration of basaltic rocks and anorthosite, caused by continuous meteor impacts and the interstellar bombardment of atomic particles charged over millions of years.

The main characteristics of the Moon concerning the dimensions, mass and densities are now presented.

	Mass [kg]	Diameter [km]	Density [kg/m^3]
Moon	$7.35\ 10^{22}$	3479	3340
Earth	$5.97\ 10^{24}$	12742	5514

Table 1: Moon and Earth characteristics comparison

However the satellite shows more differences that make the lunar environment such diverse and harsh with respect to Earth. The next subsections explain the main aspects on how the Moon is different from Earth, and are based on information retrieved from reference [2].

2.1 Vacuum

The Moon has an atmosphere that is so tenuous as to be nearly vacuum. This provokes that the main function of the atmosphere, which is to absorb part of the solar radiation, is not present in the Moon, and the solar radiation reaches the lunar surface without obstacles.

This condition provokes many problems. One of them is that some materials such as plastics and rubber loose flexibility and become brittle due to outgassing.

Since gases conduction or convection is non-existent the cooling process of systems generating heat can be done only via inefficient radiation.

Finally this fact will also have an important impact on the next subsection's aspect: the temperature.

2.2 Temperature

During the lunar day, which lasts for two weeks, the surface temperature can reach up to +123 °C. However during the lunar night, which also lasts approximately two weeks, the surface temperature drops to -153°C.

The high oscillations in temperature between day an night are due to the vacuum condition that was previously explained. This is the main reason why the Moon shows such a wide range of temperatures. This is an important aspect to take into account when trying to develop a colony mission in the satellite, since a place to minimize the harsh conditions has to be found.

2.3 Lunar Regolith

Lunar regolith also presents some characteristic that makes its usage more challenging. In fact, some studies revealed that it is highly abrasive (particles can scratch hard materials), adhesive (particles stick and coat materials), and cohesive (particles stick to each other). The reasons of this characteristics can be due to the way this dust was formed and the lunar environment (vacuum, radiation).

Therefore, in order to survive and be able to make a successful mission on the surface of the Moon, the hardware has to be dust tolerant.

2.4 Gravitational force

The gravitational force has also an impact on the mission. It is one sixth of the gravity acceleration of the Earth. It basically means that everything weighs six times less. For example of a terrestrial excavator needs to be used in the Moon, the force applied to rip the same amount in the surface would be six times greater. This would required considerable stronger machines than what we are used to in Earth.

Testing the ISRU technologies on Earth is a difficult challenge since it is hard to reproduce the previously explained Moon conditions.

3 Analysis of the existing ISRU technologies

The study of the possibility of having a human colony inhabiting the Moon autonomously without the constant resupply from Earth depends on the existing technology of using the in-situ resources of the Moon, covering the basic needs of the crew during their stay. This crew would need:

- A physical place to stay, and sleep when not exploring the Moon. This would require:
  - Building structure built with 3D printing. Also the combination of 3D printing and an inflatable system could be an option.
  - Same Earth atmospheric conditions obtained by oxygen production.
- Available food and water. This could be obtained with:
  - Water production from lunar soil.
  - Biomass production system.
- Available technology for possible needed transportation of in-situ production.

The concept and methodology used by each of these technologies to these needs will be now analyzed.

3.1 Oxygen extraction

Being capable of extracting and producing oxygen is a key point for the mission so that human life can be sustained long-term.

As it was previously explained in the previous section, being the lunar south pole location the suitable one for the mission, and being it in the lunar mare, the technology and methodology to produce oxygen will need to be useful and adapt to the composition of that kind of surface.

3.1.1 Classical approaches dependent on feedstock

Most of experimental approaches share the same characteristic of needing particular conditions of the feedstock in order to obtain high amount of oxygen. As it explained in reference [1], this is the case of: reduction with hydrogen and sulphuric acid treatment.

<u>Reduction with hydrogen</u>:

This method needs a feedstock with high concentration of iron oxide, which can be ilmenite, and a temperature up to 900º.

$$FeTiO_3 + H_2 = Fe + TiO_2 + H_2O$$

As it can be seen, the primary product is water, which can be used to generate separately oxygen and hydrogen by applying electrolysis.

Sulphuric acid treatment:

This reaction uses an ilmenite-rich feedstock. The material used in the reaction will be mixed with sulphuric acid to produce iron sulphates, titanium sulphates, and water:

$$FeTiO_3 + 2H_2SO_4 = FeSO_4 + TiOSO_4 + 2H_2O$$

The the product will be diluted with water and cooled so to filter out the iron sulfate and obtain just titanium dioxide and sulfuric acid:

$$TiOSO_4 + H_2O = H_2SO_4 + TiO_2$$

Finally the iron sulphate is electrolysed in aqueous solution in order to obtain oxygen, hydrogen and recover the sulphuric acid:

$$FeSO_4 + H_2O = Fe + 0.5O_2 + H_2SO_4$$

3.1.2 Classical approaches dependent on temperature

On the other hand there is another method for which the feedstock is not an issue, but its "success" depends on the temperature. According to reference [2], this is the case of: vapour phase pyrolysis, reduction with methane and electrolysis of molten regolith.

Vapour phase pyrolysis:

This method can be applied with several lunar feedstocks, but in this case the main issue would be the high temperature that is needed to obtain a satisfactory amount of oxygen (2000 ºC). This excess of temperature is due to be able to vaporise and decompose some of the metal oxides:

$$FeTiO = Fe + TiO_2 + 0.5O_2$$
$$MgSiO_3 = SiO + MgO + 0.5O_2$$
$$CaSiO_3 = SiO + CaO + 0.5O_2$$

Depending on the duration of the process and the temperature, the oxides of magnesium, aluminum and calcium can decompose to obtain a 50 % of oxygen.

Reduction with methane:

In this approach, since iron oxide and silicon oxide may be reduced, different types of feedstock can be used. However similarly to the previous case, the operating temperature during the reduction is high and around 1600 ºC, where the maximum oxygen yield is around 50 %:

$$FeTiO_3 + CH_4 = Fe + TiO_2 + CO + 2H_2$$

$$MgSiO_3 + 2CH_4 = Si + MgO + 2CO + 4H_2$$
$$CaSiO_3 + 2CH_4 = Si + CaO + 2CO + 4H_2$$

In the next step of the reaction, the formed carbon monoxide and hydrogen formed are added to an extra amount of hydrogen, to be converted into methane and water through a nickel catalyst:

$$CO + 3H_2 = CH_4 + H_2O$$

Finally the methane is then re-used and the water electrolysed.

Electrolysis of molten regolith

This is the so-called Magma process. For the electrolysis of molten regolith an electrolytic cell at temperature near to 1600 ºC is used. Applying a potential enables metal deposition at the cathode and oxygen at the anode:

$$\begin{cases} \text{Anode:} \quad O^{2-} = 0.5O_2 + 2e^- \\ \text{Cathode:} \quad Fe^{2+} + 2e^- = Fe; \quad Si^{4+} + 4e^- = Si \end{cases}$$

The advantages of this process is that multi-component lunar feedstocks can be used. This feedstock characteristic allows that, increasing the applied potential in steps, selective winning of metals according to their oxide stabilities is possible. The limits of the extractable oxygen during the process is around 50 %. However an important drawback would be the high temperature needed for this process.

3.1.3 Novel approaches

Electrolysis of solid lunar regolith

According to reference [2], this oxygen extraction method is based on the FFC Cambridge Process, which is an electrochemical method where solid metal compounds, usually oxides, reduced to the respective metals or alloys in molten salts. This reduction happens cathodically and tipically at high temperatures (900ºC).

The set-up consist in a cell with a cathode and an anode. The metal oxide body is the cathode, while the carbon-based material is the anode. In this conditions the oxide ions O^{2-} are ejected by the cathode, being discharged by the anode. This will consist in the formation of CO and CO_2 in the anode, which are released as a gas. So in this process the whole oxide reduction happens at the cathode.

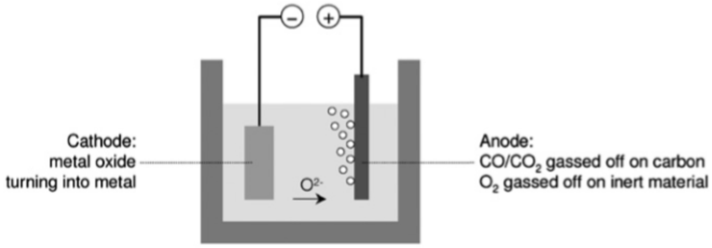


Figure 1: Schematic FFC cell [2]

The overall scenario happening in the cell can be summarized with the following reactions:

$$\begin{cases} \text{Cathode:} \quad MeO_x + 2xe^- = Me + xO^{2-} \\ \text{Anode:} \quad C + O^{2-} = CO + 2e^-; \quad C + 2O^{2-} = CO_2 + 4e^- \end{cases}$$

So, basically the FFC process uses carbon-based anodes in order to discharge oxide ions and then remove them as carbon oxides. Since for lunar materials the desired product is oxygen, a material should be found in order to be able to still produce oxide ions but removing molecular oxygen, as it is showed in the following anode reaction:

$$\text{Anode:} \quad 2O^{2-} = O_2 + 4e^-$$

Many experiments have been carried out in order to find the right material to fulfill this reaction, but only two were promising:

- **Doped tin oxide (SnO_2):** It is a commercial available material which is found to generate oxygen when used as an anode in a calcium chloride environment. The drawback are that its lifetime is around two hours because of the erosion and also its conductivity is compromised during the process.
- **Solid solution of calcium titanate and calcium ruthenate ($CaTi_xRu_{1-x}O_3$):** Its conductivity varies from metallic to semi-conducting depending on the ratio amount between ruthenate and titanium that is used. It is proved to generate oxygen with no significant erosion or passivation.

Also different experiments were carried out with lunar simulants and ilmenite in order to see the effect for materials relevant for the ISRU technology. The results were presented and two important conclusions where made:

- The oxide powder feed should have a pretreatment based on the pressing tiles and their sintering into their compact oxide bodies.
- The solid metal product tends to remove part of the quantity of the electrolyte, which should be replenish with fresh salt (which is supplied from Earth).

3.1.4 Implementation of the methodology

Nowadays there have been several attempts and tests trying to make possible the oxygen extraction using the methods previously explained. Basically the two methods that have been used are: hydrogen reduction and carbothermal process. Now some examples of actual machinery will be presented.

For the first method, the most notorious cases are: PILOT, ROxygen, Concentric Hydrigen Reduction Reactor, and RESOLVE. All of them used the same process previously explained in the hydrogen reduction section.

A) PILOT

PILOT is a project carried out by NASA and it stands for Precursor In-Situ Lunar Oxygen Testbed. The system was built to scale to get an oxygen production near to the 1000 kg per year, able to withstand the lunar conditions [4].

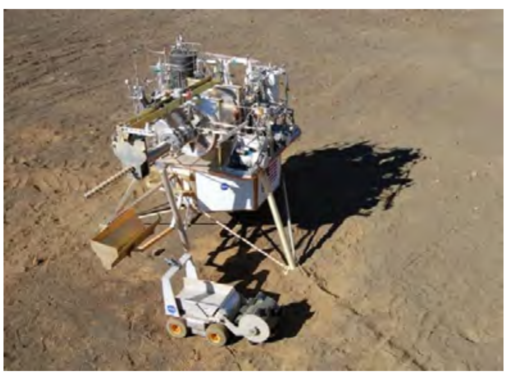


Figure 2: PILOT in Hawaii in 2008 [4]

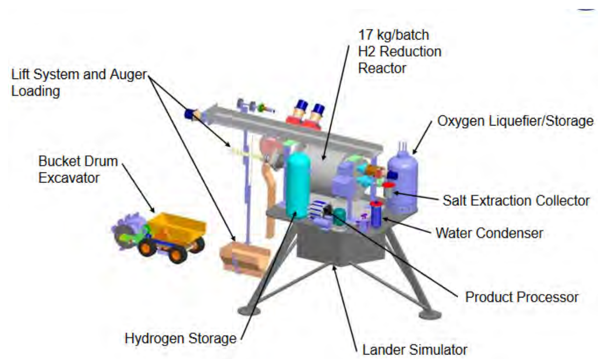


Figure 3: PILOT's schematic [4]

In Figure 3 can be seen the different parts of the system. After the bucket drum excavator has collected the necessary feedstock the process begins [4]:

- An auger (placed at the bottom of the hopper) is the one that introduced the regolith into the reactor.
- Inside the conical reactor is where the fluidization of the soil happens. In fact it will be mixed with hot hydrogen.
- Once the water is produced, it will be pass through a purification module and the electrolysis will began separating oxygen and hydrogen.

Different field tests have been carried out. One of them was in Hawaii in 2008 where the following conclusions were made [3]:

- The system was able to successfully produced oxygen from regolith
- Each batch was able to admit 15 kg of regolith

- Produced oxygen yields of 1 wt% of processed regolith

B) ROxygen

This is another project by NASA. It uses the same principle as PILOT but in this case it is design to a scale to produce 660 kg/year which is 2/3 of PILOT performance [5].

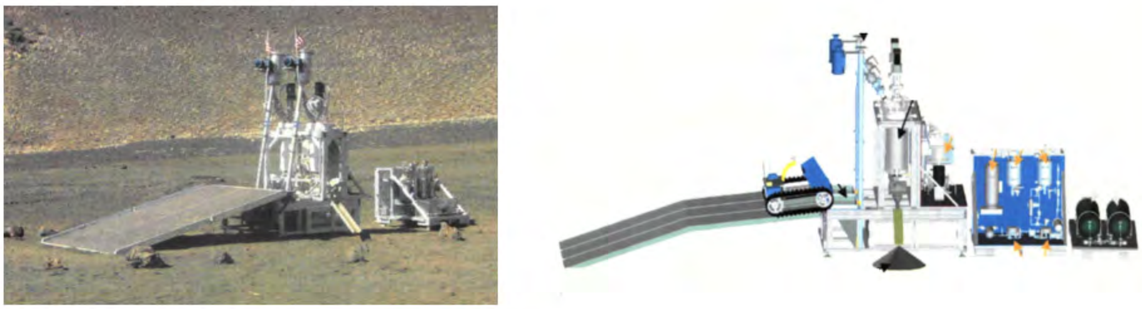


Figure 4: ROxygen in Hawaii in 2008 and its schematic [3], [Google]

The schematics of the Roxygen system are shown in Figure 4. It is composed by a cylindrical reactor which contains an internal auger system. This system fluidizes the regolith to favor heat transfer. The vertical configuration is based on the gravity principle to enable the feeding of regolith into and out of the reactor [5].

Different field tests have been carried out. One of them was in Hawaii in 2008 where the following conclusions were made [3]:

- The system was able to successfully produced oxygen from regolith
- Each batch was able to admit 10 kg of regolith
- Produced oxygen yields of 0.2-0.5 wt% of processed regolith

C) Concentric Hydrogen Reduction Reactor (CHRR)

The Concentric Hydrogen Reduction Reactor also is a NASA project, and operates with the same method as the previous cases.

Figure 5: CHRR Chamber [3]

It consists of concentric cylindrical chambers, and their main use is to allow the exchange of heat between the cold regolith that is going to be introduced in the system and the hot one that is being processed. It maintains the regolith in a fluid state and mixes it with hydrogen [3].

The test that have been done in the large reactor provided oxygen yields in the range 0.2% – 0.5% by mass of regolith. The low yields are attributed to the operational limits of a contaminant scrubber [3].

D) RESOLVE

Now we have another example of a project that has been also tested in Hawaii, simulating the lunar conditions. This project could be considered one of the most complete in terms of analysis of oxygen extraction. It is the RESOLVE mission carried out in 2012. The name stands for Regolith and Environment Science, and Oxygen and Lunar Volatile Extraction (RESOLVE), and it was carried out three different times, but the most recent was in 2012. RESOLVE is an internationally developed payload projected by NASA and CSA. The two main objectives of the the RESOLVE project for a future lunar mission are [7]:

- To verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials.
- To demonstrate the ISRU Hydrogen Reduction Process to extract oxygen from lunar regolith.

During the nine-days test in Hawaii, back to 2012, the rover looked like this:

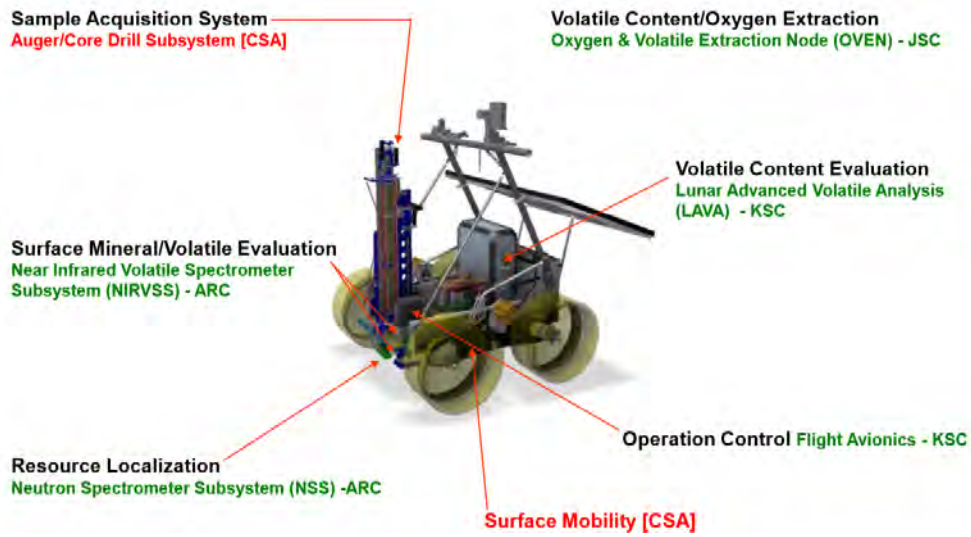


Figure 6: Schematic of the RESOLVE functionalities [7]

As it can be seen in the schematics above, the RESOLVE system have different subsystems with different functionalities [7]:

- **Sample Acquisition System**: It is a Auger/Core drill that collect and transfer subsurface material down to 1 m below surface. It also measure geotechnical properties of the material while drilling.
- **Surface Mineral/Volatile Evaluation**: It detects form of water (ice/hydration) in auger tailings.
- **Resource Localization**: It locates hydrogen down to 1 meter below the surface.
- **Surface Moibility (CSA)**: This subsystem carries RESOLVE payload and provides power, communication and thermal management.
- **Operation Control**: It is a space-rated microprocessor that controls the subsystems and manages data.
- **Volatile Content Evaluation**: It provides hydrogen for oxygen extraction. It also performs analysis in under 2 minutes to measure water content in evolved gas.
- **Volatile Content/Oxygen Extraction**: It accepts samples from Sample Acquisition System and heat the samples to extract oxygen.

Finally, there is a fifth equipment which is able to produce oxygen using a different method: the carbothermal process.

E) Carbothermal Reduction Process

This project has been carried out by ORBITEC. ORBITEC built and tested the Carbothermal Regolith Reduction Module to process simulated lunar regolith using concentrated solar energy. This module includes: the Regolith Hopper, Carbothermal Reduction Reactor and the Processed Regolith Exit Valve [11].

Figure 7: Carbothermal Reduction Module and Solar Energy Collection [5]

The regolith needed for the process is collected by the Regolith Collection and Delivery Module. After that it is transferred from the Regolith Hopper to the Carbothermal Reduction Reactor. From there the system exploits the reduction with methane method which was previously explained to produce oxygen [11].

The Solar Energy Module that can be observed in Figure 7 is used to locally heat and melt the regolith in a methane gas environment in order to produce carbon monoxide and hydrogen. This is achieved by delivering thermal energy to the system [5].

3.2 Water production

Water is an essential element for a manned space mission. Since carrying water from Earth would not be an option due to the huge amount of periodical launches that would be needed to provide to the crew leading to an incredibly high cost. Therefore, alternative methods have to be implemented to obtained the required water.

An important fact to know about the Moon is that around 5% of lunar crater's soil consists of water ice. This fact was discovered in the NASA's LCROSS mission. This mission was carried out in 2009, there were some important discoveries concerning water in the Moon. Specifically it was detected the existence of significant amount of iced water and volatile gases such as hydrogen, helium and nitrogen. This iced water and gases can be found in the permanently shadowed craters of the Moon's poles [2]. The reasons of this presence in the Moon can be [2]:

- Water comes from outer sources such as water-bearing comets striking the surface.
- Water is generated by the conditions of the Moon. For example a possible explanation would be that the formation of water comes from the interaction of the solar wind with rocks and soils of the Moon.

This discovery gives the chance to study different possibilities and approaches to extract both water and oxygen so to make more independent the future colonies inhabiting the Moon.

3.2.1 Processes to produce water

In order to extract the water from the lunar soil there exist three possible approaches:

- Chemical reaction that also uses the electrolysis approach, which includes some drilling activities into the rocks and so generating a mine water.
- Using microwave technology to undo the ice and get the water in gaseous form.
- Recycle it from the Water Recovery System.

The previous methodologies will be now described.

Chemical approach

It has been discovered that taking the Moon regolith, and adding some hydrogen, water can be formed, since it will react with iron oxide (reduction with methane principle).

In order to get the hydrogen, electrolysis can be used. The electrolysis method has been explained in the previous section in the oxygen extraction. It works exactly the same for the case of water, allowing at the end of the reaction to split into hydrogen and oxygen, so to be used for this purpose or other such as rocket fuel or air supply for the colony.

In order to do so, a water mine should be created in order to extract the needed feedstock from the lunar soil for the reactions that have to be performed. This extraction has to be operated with some drilling machinery. Some of this equipment or tools are [2]:

<u>Lunar scoops</u>

Scoops are instruments used to get loose soil. In fact it cannot penetrate into the solid lunar soil nor rocks, but just collect the weighter parts. For this reason its main usage is to collect samples for later investigation and research.

<u>Lunar drills</u>

Lunar drills accomplish what the scoops cannot do, and so penetrate the heaviest rock in the Moon and so getting to the potentially useful depth where a specific material condition can be found. Some of the technologies used for this scope are enumerated below:

- **The Moon-breaker**: It is the simplest lunar drill. It is a rotary-percussive system and similar to the Apollo Lunar Drill, but requires less power.

- **Lunar Pneumatic Excavator**: This is a pneumatic instrument that works following the principle explained in Badescu's book which says: "If a nozzle is sufficiently well sealed, injected gas will accelerate the soil particles along the tube and move them to a collection bin (Zacny et al. 2004). A cyclone separator like the ones commonly used on Earth would easily separate particles from carrier gas".
- **Lunar Percussive Excavator**: These are like terrestrial excavators, such as backhoes, but much larger and heavier since they have to create six times the force needed in Earth, for the gravity reasons.

Once the feedstock is ready, the proper machinery is needed to process it and extract the water from it. It has been proved that the equipments to produce oxygen using the hydrogen reduction previously explained could be used for this purpose. In fact the first step followed by the hydrogen reduction method is to heat up pure hydrogen with minerals containing iron oxides, to form water vapor. So it would be just needed a condenser to transform the vapor into liquid water.

Microwave approach

According to reference [18], the microwave approach is a method that allows to extract the water without drilling and so mining the lunar soil.

This method basically consist in using microwave heating to cause the water ice, which is present in the lunar permafrost, to sublimate and so to convert it into water vapor. So the water vapor can be collected and the condensed into liquid water.

One of the advantages of this method is that eliminating the need of digging, it would reduce the dust problems involving the astronauts and the machinery. Also it could work better in the Moon due to its near-vacuum environment.

There has been some studies and actual experiments showing this possibility to generate water from lunar material. This is the case of NASA, that with Ed Ethridge and its team they prepared the following experimental setup at the Marshall Space Flight Center in Huntsville, Alabama, to prove this method.

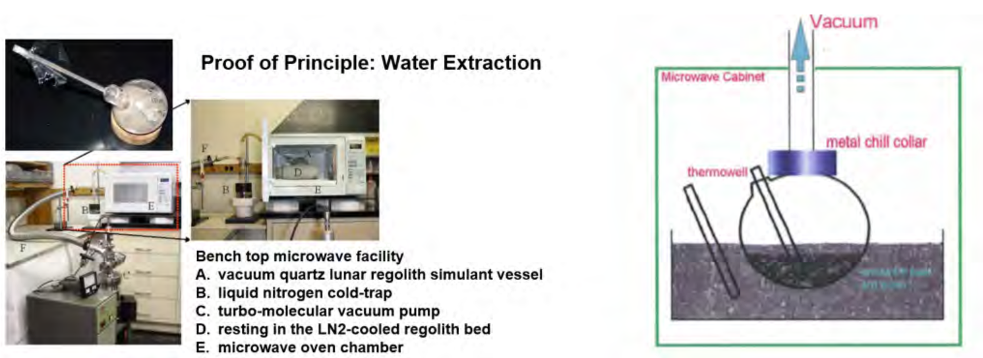


Figure 8: Ed. Ethridge's experimental setup and Quartz vessel schematic [18]

In order to simulate lunar conditions in terms of temperature and vacuum, a microwave-transparent vacuum vessel was added within the commercial oven cavity. Once the conditions were prepared the lunar regolith simulant was placed into the quartz vessel and added a percentage of water. Supplying a microwave power of 1200W the experiment was able to start.

This experiment showed very promising results such that at least 95 percent of the water added to the simulant was extracted (vaporized out of the soil) with 2 minutes of microwaving.

Water Recovery System

This method is already used in the space programs nowadays. For example the ISS (International Space Station) has incorporated since 2008 a very efficient Water Recovery System prepared by NASA. This system is essential for the crew to conserve and provide potable water. It recovers urine in addition to humidity [20].

Figure 9: NASA WRS of the ISS [20]

The elements that constitute together the NASA WRS are the water processor assembly (WPA) and the urine processor assembly (UPA). Their interaction consists in: when the crew urine is recovered, the UPA distills it and then fed the WPA along with humidity condensate/wastewater. The water will be used by the crew as a potable source, and is fed to the oxygen generation assembly (OGA) as a source of electrolytic oxygen that is returned to the spacecraft cabin [20].

The optimized process capacity of the WRS to is approximately 7 liters of condensate daily and it is also able to produce 12 liters of potable water per day [20].

3.3 Biomass production

In order for the colony to survive in the Moon is to have food available to cover their needs. Nowadays a lot of possibilities for this issue were discussed. One of them was just carrying food from Earth, which is very expensive since many launches have to be made. Another one was to bring a 3D printer in order to print their the food, but it would also be expensive since a lot of things to use as "food ink" should be carried periodically from Earth. Finally the most plausible option would be to create an orchard in order to grow plants in-situ. Even this option carries some difficulties since a similar Earth environment has to be created without compromising other factors of the mission. There have been some studies analyzing this option and they will be now presented.

3.3.1 EMCS - First European plant growth experiment

The European first plant growth cultivation system experiment to ever be carried out is the EMCS (European Modular Cultivation System). It has been set in the International Space Station in 2008, in the ESA Columbus Module [22].

Figure 10: EMCS inside ESA's Module [22]

It did not have the size nor the capacity to allow the growth of vegetables or other plants for food production. But it has been an important element to some different European plant growth and plant physiology experiments.

The EMCS contains two rotors that allow to have different levels of gravity to the containers (EC) of the experiment.

The module also provide a simple life support system, reservoirs, lamps and a video camera system for experiments.

3.3.2 EDEN-ISS

EDEN-ISS is an European project which is still in process. It started in 2015 and will be finished in 2019. It consists in creating a facility which allows the plant growth in space environments such as in the Moon. The project shows the availability of advanced controlled environment agriculture technologies and its main purpose is to develop a rack-like facility leading to a short-term safe food production and operation on-board the ISS (International Space Station). For this reason this project could be extrapolated to our Moon case.

Figure 11: EDEN-ISS structure [23]

The main aspects to be analyzed and for which the facility consist of are [23]:

- **MTF (Mobile Test Facility)**: It is the whole facility, which can be divided into three different sectors
  - Cold porch: It is a small room where storage is provided and also used as preventing cold air getting to the cultivation area.
  - Service Section: It is where the ISPR is placed. ISPR stands for International Standard Payload Rack and it is where the control, air management and the thermal control are placed.
  - Future Exploration Greenhouse: It is the main plant growth area. It is structured with multilevel plant growth racks operating in a precisely controlled environment.
- **ISPR Cultivation System Preliminary Design**:
  - ISPR Structure Subsystem: It is the physical structure where multiple configurations in the rack development process can be implemented. It is basically the place where all the modules will interact together.
  - ISPR Illumination Subsystem: It is the lightning system. It consists of controllable water cooled LEDs.
  - Atmosphere Management Subsystem and Thermal Control Subsystem: It guarantees each volume growth with an independent air management system to provide it with the proper conditions.
  - Nutrient Delivery Subsystem: It consists of reservoirs and actuators that work together to guarantee the proper distribution of water and nutrient solution to the areas of the substrate.
  - Command and Data Handling Subsystem: It is the subsystems in charge of collecting the data from the sensors and transform it into commands for the system.
  - Power Distribution and Control Subsystem: The power will be sent from the MTF to

the ISPR. Then it will be properly distributed to the utilities by signal of the Command and Data Handling Subsystem.

- **ISPR Preliminary Crop Selection**: The growth difficulties in such difficult environment make the crop selection very limited, allowing just a few crops to be cultivated such as dwarf tomato, rucula and lettuce.

All the aspects described work together and ensure a successful cultivation in a closed environment with possible space application in a near future.

3.3.3 Biomass production system (NASA)

The BPS is a environmental control system designed by NASA which provides plant growth in the absence of gravity. This project was taken in order to gather information and checking the viability of implementing this proposal to ensure the survival of the colony in a space environment such as the Moon [23]. The research areas were divided into:

- Test of the system as potential hardware for the human missions in space
- TVT of the system (Technology Verification Test)
- Comparison of the system plant growth with respect to the Earth one

Figure 12: Biomass Production System [26]

The main objective of the BPS was to be able to maintain at least for 90 days a plant growth in micro-gravity conditions. Two experiments were included [26]:

- **Technology Verification experiment:** It consists in the validation and testing of the hardware systems and protocols to be used in micro-gravity environment.
- **PESTO experiment:** It is Photosynthesis Experiment and System Testing and Operation experiment. It consists in the effects of micro-gravity in terms of the metabolism and photosynthesis.

In order to carry out all the necessary experiments *Brassica rapa* was used as test plant species. First this species were contained in a BPS plant growth chamber (PGC) when they were already started to grown on the ground and the consequent photosynthetic development began. These results were then compared with previous BPS experiments. This was implemented in a period of 73 days where also other kind of plants were tested to grow in micro-gravity conditions.

These studies allows to analyze the possibility of designing the future plant growth units for space missions. This research is linked to "Farming in Space" which studies the basic principles of plant biology, agricultural production, ecology, and the space environment.

3.3.4 Prototype Lunar Greenhouse (LHG)

One of the most advanced project in terms of biomass production for a moon-based mission has been carried out by the University of Arizona, with fundings from NASA [27]. The controlled environment agriculture center of the university designed and manufactured an innovative hydroponic plant growth chamber.

Figure 13: Prototype Lunar Greenhouse Capsule [27]

As it can be seen, it consists of a round tube within which different crop species such as lettuce, strawberries, tomatoes, or sweet potatoes are grown. For now it is focused on using plants and so sustaining a continuous vegetarian diet for astronauts. In addition of this food, it also provides other important features such as air revitalization, water recycling, and waste recycling for the crew. In fact fertilizers, water and CO_2 are added, to keep the atmosphere and soil regulated.

3.4 3D printers

The 3D printing technology is an additive manufacturing process to create 3D objects from computer models. It is a relatively recent discovery and it is still in development. Particularly if we talk about space missions. For these purposes this printing method had to be adapted to space conditions, and so to micro-gravity.

It was in 2014 when Made In Space's 3D printer (Zero-G printer) when the first manufacturing device in space. From there on, the 3D printer started its big development in the space sector and started to be considered a key point for future space missions. In fact the main uses of the 3D printing technology in a lunar mission would be:

- To create objects that are needed for a particular task. For example if there is some problem with a tool or a specific object that is being used in a specific activity, it can be easily replaced with another one made with the 3D printer. This way the issue will not cost time to the crew and they can carry on with their activities without waiting for some replacement form Earth which could cost a big amount of time.
- To build shelters, roads or whatever structure is needed. In fact the crew is not able to accomplish this kind of activities.

3.4.1 3D printing methodologies

In this section the most important and representative 3D printing methods that can be feasible in a lunar mission are presented.

D-shape 3D printing

This method consist in a large scale 3D printer in order to print objects the size of buildings. This machine requires a special "ink" in order to print object. Its mechanism uses an additive process so to build 3D objects on a bed of regolith placed under the printer. This allows that complex structures such as arches can be printed. This process may present some drawbacks such as the difficulty of printing using injection in vacuum environment.

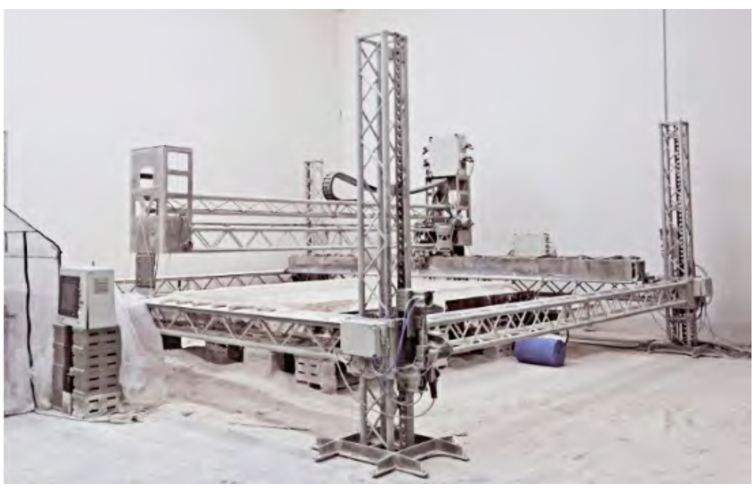


Figure 14: D-Shape Machine [Google]

The company Monolite UK and in specific Ceccanti have been very active to promote and improve this technology through these years. These are the most important characteristics of this printer [30]:

- The bider jetting process is used. It consists in creating a powder layer and then put on it binder making the mix to solidify. This process is repeated for each layer until getting the final desired shape.

- The final object is divided in several layers, and it is an external computer which is connected to the printer to guide the binder jet.
- A flat and strong terrain is needed to evenly support the weight of the machine and to create the proper powder-bed.
- When the printing is finished the powder support has to be extracted to obtain the final structure.
- The printer is composed by 4 pillars, each one interconnected by beams. These beams are at the same time interconnected by two beams. There is where the ejecting binder will be placed.
- The binder beams can move upwards and downwards, but also along the beams, so it can reach each point of the powder-bed of each layer.
- The movement is allowed by small electrical engines placed in the pillars.

Solar printer

This method is used to create bricks or shapes in order to be able to build a shelter. In fact it would consist in creating the material to be used in one place and then to transport it to the place where the shelter wants to be built. For this reasons the created parts will be relatively small (similar to bricks) and the building process will be adding the bricks in such a way to create the desired structure.

This printer has been created using the principle of getting benefit from the two most important resources that can be found in the Moon: the sunlight and the moondust. It is basically an oven in which very thin layers of the moondust are baked on a table appositely placed in the 3D printer at very high temperatures. This temperature is achieved by using several curved mirrors to focus sunlight.

Nowadays we have already relatively small examples and samples made by this technology, even though they are not prepared for the requirements that a lunar mission would require.

The pioneer of this 3D printing method is the German designer Markus Kayser who developed an experiment in the desert, back in 2011. He basically built a machine that making use of sand as powder and concentrating the thermal energy from the sunlight could build two objects. The facilities he used where simple as shown in figure below:

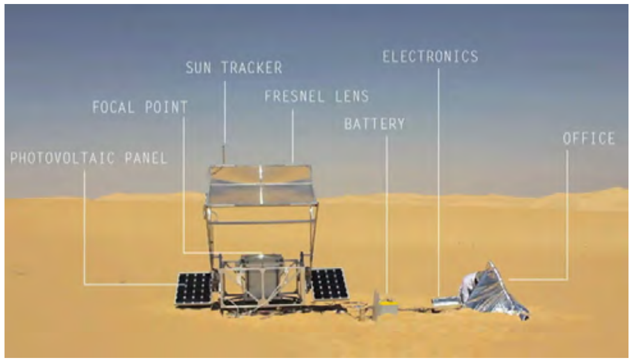


Figure 15: Solar 3D printing machine [Google]

Later on, some other experiments were carried out on a bigger scale and using more accurate lunar conditions, like using actual lunar powder simulants [33]. The most notable example is the creation of a 3D printed brick from moon-dust using focused sunlight, which can be appreciated below:

Figure 16: Brick 3D printed from moondust using focused sunlight [33], [Google]

This experiment has been carried out at the solar furnace of the DLR German Aerospace Center facility in Cologne, Germany.

Figure 17: Mirrors of the DLR [33]

This center has 147 curved mirrors focus sunlight into a high-temperature beam to melt the soil grains together. Since sometimes the weather in northern Europe does not always help and do not give the required sunlight, the needed light is sometimes simulated by an array of xenon lamps more typically found in cinema projectors. As mentioned before this is just the start of this technology, but it will be implemented in the future since it has been proved that this kind of method is feasible. Now it is turn of other companies such as ESA or Regolight to follow and develop this 3D printing technique [33].

Contour Crafting

Professor Behrock Khoshnevis invented another useful form of printing, the Contour Crafting. It basically consists in a digitally controlled construction process. In fact it fabricates structures or components from computer models, so designed digitally. It also used the layered fabrication method, having a guiding nozzle who ejects and extrudes the concrete. In order to work properly it needs something to smooth out the terrain so it can print properly. This action is carried out by a trowel that follows the nozzle. There can be two ways to implement this technology. The first one is having a moving printer such as the one of Figure 18, so it can move and advance to print in different places (basically the printer is on a rover). The second option is having a disposition similar to the D-Shape printer, showed in Figure 19.

Figure 18: CC rover [34]

Figure 19: CC fixed [34]

The main problem it could appear with this technology is the difficulty to build structures with complex geometry such as arches. In this sense the D-Shape allow a wider range of forms like shallow arches. The only option for the CC to do that kind of form would be to print the arches horizontally on a flat surface and then move them robotically in the desired configuration.

This 3D printing technology is still being studied and we have not any example or application in the real world yet. So it can be a little bit difficult to study its viability right now. But it will be surely developed in the near future.

3.5 Transportation rovers

All the technologies we have described above that produce the necessary parameters for the crew to survive in the Moon without depending on the Earth have a common aspect: they all need feedstock, and so the regolith that can be found on the surface. But who takes the needed amount to the machinery?

Along the years different rovers and robots have been created and developed to carry the moondust from one place to another. Even to dig on the surface to get more material. The main aspects to analyze the rovers are:

- How much material they can store and then deliver
- The speed they can dig and recollect the material

- How they can travel through the surface without stability problems

So the rover's efficiency depends on several parameters. This is why there is no a winning design for it. Here are the most representative and efficient types of rovers that can be found:

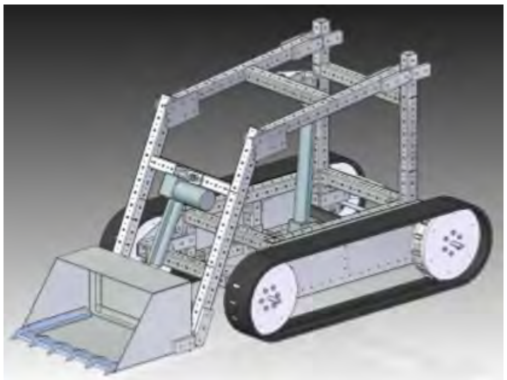


Figure 20: 2010 Auburn Mining Design [40]

Digger Arm Rover

- This is the simplest design.
- It consist of a digger arm that just collects the moondust placed on the surface of the terrain.
- The way it is designed could lead to some instabilities for certain obstacles in the terrain.
- It can store up to 10kg of moondust.

Figure 21: Bucket Drum Excavator [4]

Bucket Drum Excavator

- This is a more elaborated design.
- It can collect the moondust by rotating the drum that has on its front and store the material there or on the dump bed.
- It can store up to 18kg of moondust on the dump bed and 10kg on the drum load.
- It is able to go deeper in the surface than the previous design.

Figure 22: NASA RASSOR 1.0 [Google]

NASA RASSOR 1.0

- This is the most innovative design.
- It can collect the moondust by rotating the drum placed at the extremes.
- The way it is designed with the movable arms makes the rover able to adapt to almost every kind of surface it may encounter.
- It can store up to 20kg of moondust.
- It is able to go deep in the surface.

3.6 Power generation

All the equipment that has been described and analyzed in the previous sections cannot work if they do not have a power source. What would be the easiest way to produce the required power continuously for all the machinery is going to be used in the mission?

The solar panels seem to be the best option since, they just need solar thermal energy to store the required energy. As we know, the mission would be located where the sun is a powerful element. Nowadays there is any available technology that would allow to create the solar panels in the Moon. Therefore if we want the mission to exists we are forced to carry from Earth the solar panels that are needed for each equipment.

4 Mission Analysis

In this section the requirements of a long-term mission will be set and identified in order to be able of analyzing the viability of the technology that has been previously described. Doing so we will be able to determine the in-situ technologies that could fulfill the requirements and be potentially used in a real scenario.

4.1 Mission parameters

The following subsections present the inputs needed to run a simulation of the mission. A possible simulation of the a mission would require to take into account several aspects or several modules: environment, crew, air, food, power, and water. In each module we are able to introduce some inputs to define our mission.

The idea is to carry out a long-term mission in the Moon, possibly with 6 months of duration. The ideal mission would be a closed-loop one. It means that it would consist on a continuous operation, with all resources produced in-situ for the mission. Its location would be the South Pole of the Moon. This region has been chosen due to two important advantages that the moon-base may encounter if placed there:

- The presence of permanent sunlight is a key factor since it can be beneficial for several processes to be carried out during the mission such as:
  - The generation of power from solar panels.
  - Some processes may need high temperatures, which can be reached easier in that region.
- There exist some permanent shadowed areas due to the existence of some craters. In these dark regions there is presence of hydrogen which is an important element for some processes such as the production of oxygen or water.

Most of the calculations with the input parameters needed to determine the output for the mission has been adapted for our purpose following the information contained in a Research project carried out by the University of Würzburg, called Moon base 2030, and the NASA Human Integration Design Handbook.

4.1.1 Environment

The crew is going to a hostile environment and will need to stay there for a long period. So it is mandatory to provide them with a well tempered, pressured and with a suitable mixture of gases atmosphere.

The environment contains air that is consumed by either people or crops. Air contains a mixture of gases. In our simulation these gases are oxygen (O_2), carbon dioxide (CO_2), nitrogen (N), water vapor (H_2O), and other minority gases.

When the initial composition of the gases is set, then according to the consumption and generation of each gas form the crew and corps, the composition will change.

The environment composition will be the the same as the Earth atmosphere:

	O_2	N	H_2O, CO_2, Ar
Crew quartes	21 %	78 %	1 %

Table 2: Environment Inputs Table

4.1.2 Crew

The crew module has several parameters to be defined. Some of them about their condition characteristics such as the number, gender, age and weight. Other about their cycle, which is defined by a set of activities (sleep, maintenance, recreation, etc.). As they do so they consume O_2, food and water, and produce CO_2, dirty water and solid waste. The amount of resources consumed and produced varies according to crew member attributes and their activities. So they are connected to the previous environment that contains an atmosphere that they breathe. An example day scenario may consist of 8h of sleep, 14 hour of leisure and 2h of workout. The inputs that define the crew module of our mission are summarized in the table below.

	MEMBER 1	**MEMBER 2**	**MEMBER 3**	**MEMBER 4**
GENDER	Male	Male	Female	Female
AGE	35	40	35	40
HEIGHT	1.8 m	1.7 m	1.7 m	1.6 m
WEIGHT	80 kg	70 kg	60 kg	50 kg
ACTIVITIES	Leisure (14 h) Exercise (2 h) Sleep (8 h)	Leisure (14 h) Exercise (2 h) Sleep (8 h)	Leisure (14 h) Exercise (2 h) Sleep (8 h)	Leisure (14 h) Exercise (2 h) Sleep (8 h)

Table 3: Crew Module Table

For an average human being, the density of its body is about 1010 kg/m^3. This density value can be used to calculate the volume of each crew member's body. The following results have been obtained:

	MEMBER 1	**MEMBER 2**	**MEMBER 3**	**MEMBER 4**
VOLUME [m^3]	0.079	0.069	0.059	0.049

Table 4: Estimated crew members' body volume

4.1.3 Human Metabolism

To see how much oxygen, water or food has to be provided to the crew, it is useful to see how the human metabolism works. The values of the human metabolism can be differentiated in three blocks:

- **Solids**: It includes food consumption or fecal waste.
- **Liquids**: It includes water consumption or urine waste.

- **Gases**: It includes the oxygen breathed and the CO_2 exhaled.

The next Figure shows a scheme of the three blocks interacting with the human body.

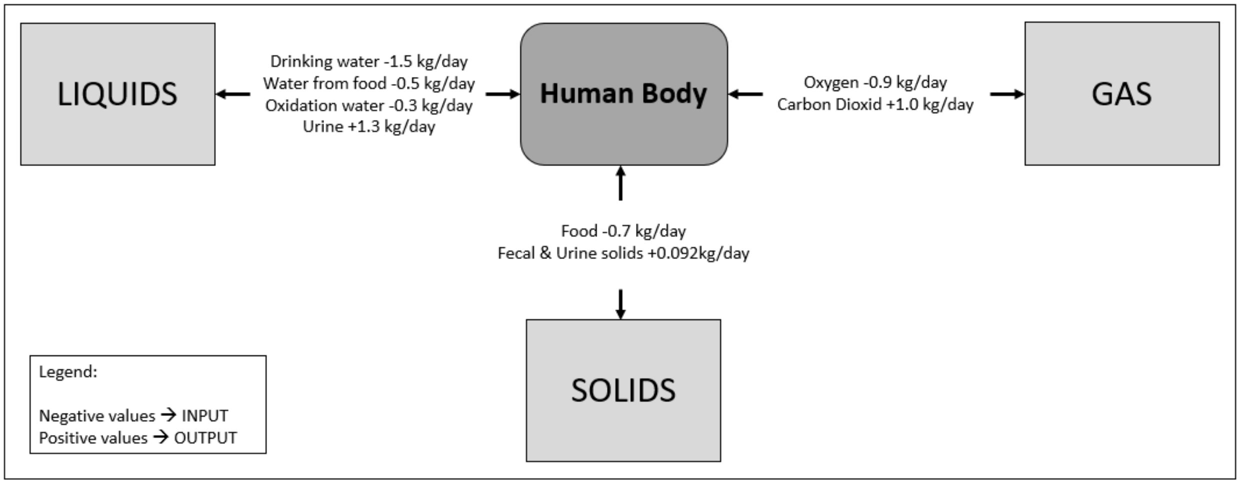


Figure 23: The Human Metabolism [42]

From this diagram, some useful data can be retrieved. Now the different blocks will be analyzed separately to determine the required inputs for the mission.

The inputs will be calculated for the whole duration of the mission (6 months) plus a margin of 2 months. This margin would be enough to consider any issue or delay that may arise during the mission.

Gases (Air)

This module is controlled by the Air Recovery System, helped with the oxygen production equipment, It basically takes in exhalant CO_2 and produces O_2 as long as there is sufficient power being provided to the system. This is done to maintain a stable environment and keep the values we already defined. We do not add any input to this module and let it as default.

The production of CO_2 and the consumption of O_2 will vary depending on the activities the crew is carrying out. The following table shows the activity related mass flows of oxygen and carbon dioxide:

Activity	**Pulse [1/min]**	**O2 [kg/d]**	**CO2 [kg/d]**
Sleep	60	0.41	0.45
Leisure	70	0.82	0.85
Exercise	140	5.11	5.65

Table 5: Activity related oxygen and carbon dioxide mass flows

From the table, the oxygen consumption in a day by a crew member can be retrieved. Since a day scenario includes 8h of sleep, 14h of leisure and 2h of exercise, the following values are found:

- Sleep O_2 consumed in a day $= 0.41\frac{kg}{d} \cdot 8h \cdot \frac{1d}{24h} = 0.1367\,kg$
- Leisure O_2 consumed in a day $= 0.82\frac{kg}{d} \cdot 14h \cdot \frac{1d}{24h} = 0.4783\,kg$
- Workout O_2 consumed in a day $= 5.11\frac{kg}{d} \cdot 2h \cdot \frac{1d}{24h} = 0.4258\,kg$

Therefore the total oxygen consumed in a day by a crew member is 1.041 kg. Since the mission will consists of 6 months plus an added margin of two months, the total oxygen required by a crew member in the mission will be:

$$O_{2,tot}/member = 1.041\frac{kg}{day} \cdot 8\,month \cdot \frac{30\,days}{1\,month} = 249.84\,kg$$

Finally considering that the total number of the crew is 4, the total oxygen to be produced in the mission will be four times the one obtained:

$$O_{2,tot} = 999.36\,kg \approx 1000\,kg$$

So the production of oxygen is no an issue anymore. But what happen with the CO_2? The CO_2 is a non-desirable element for the atmosphere needed by the crew. Since the crew is exhaling CO_2 there is the need of having a CO_2 reduction system to maintain the balance. But there can be some other environments where the situation is the opposite. That's the case of those processes than can regain the oxygen from the carbon dioxide, such as biomass production system (which will be explained later). For that case, a CO_2 concentration unit would be useful to store the CO_2 and supply it to the biomass production system in case it was necessary.

The Air Recovery System will be the one to make this balance possible and to be able to have a closed-loop, independent from Earth.

Liquid (Water)

Water is one of the most important requirements in a moon-based mission, since it covers the basic needs of the astronauts and have the following functions: drinking supply for the crew; general water usage like shower or washing; for the plants. There exists different categories for the water in a space base:

- Supply Water:
  - Potable water: It is the water with nutrients which the crew members can drink.
  - Hygienic water: It is the kind of water used for hand washing, shower, toilet flush, and pouring the garden.
- Waste Water:
  - Grey water: It consists of the water that comes from the showers and hand washbowls.
  - Black water: It is the water coming from the toilets, being flush water, urine and fecal.

The waste water can be recycle and then converted into hygienic or potable water. Obviously gray water will be far easier and more efficient to be recycled than the black one.

A person used to drink at least 2 kg of water each day. From this data, the drinking water to be supplied to the whole crew during the mission can be estimated:

- Total hydration water for the whole crew in a day= $2\ kg \cdot 4 = 8\ kg$
- Total hydration water for the whole crew in the mission $= 8\ kg \cdot 8\ month \frac{30\ days}{1\ month} = 1920\ kg$

But it was mentioned before, water is not used only for the crew hydration but also for some other purposes such as personal hygiene. Considering that the required water for personal hygiene is about 0.4 kg/day per crew member, it is obtained that:

- Total hygiene water for the whole crew in a day= $0.4\ kg \cdot 4 = 1.6\ kg$
- Total medical water for the whole crew in the mission $= 5\ \frac{kg}{member} \cdot 4\ member = 20\ kg$

Finally there is also an extra amount of water for medical usage, which is used just in case of a medical contingency, which is:

- Total hygiene water for the whole crew in the mission $= 1.6\ kg \cdot 8\ month \frac{30\ days}{1\ month} = 384\ kg$

To sum up the water requirements during the mission for the whole crew, the following table is presented:

	Required water per day [kg]	Total required water [kg]
Hydration	8	1920
Hygienic	0.4	384
Medical	0.08	20
Total water	**8.48**	**2324**

Table 6: Required water by the whole crew throughout the mission

This value is only considering the water needed by the crew. There would be another possible usage that could give an extra input to the required water for the mission: the Biomass Production System. The amount of water required for this process will be determined afterwards when the biomass equipment performance is studied and its values will be added to the requirements above.

Solid (Food)

To determine the amount of food required or to be able of designing an appropriate Biomass Production System, an analysis of the human needs has to be carried out first.

The required calories and food mass that would be required by a crew member to have a balance diet depends on the height, age, weight and gender. The following equations estimate the energy requirements of each crew member as a function of those parameters:

$$EER_{male}\ (kcal/day) = 622 - 9.53 \text{ x } Age[y] + 1.25 \text{ x } (15.9 \text{ x } Mass[kg] \ + \ 726 \text{ x } Height[m]) \quad (1)$$

$$EER_{female}\ (kcal/day) = 354 - 6.91 \text{ x } Age[y] + 1.25 \text{ x } (9.36 \text{ x } Mass[kg] \ + \ 726 \text{ x } Height[m]) \quad (2)$$

Therefore, the estimated energy per day required by each crew member of our mission will be:

	MEMBER 1	MEMBER 2	MEMBER 3	MEMBER 4
Req. Energy [kcal/day]	3092.55	2778.7	2356.9	2114.6

Table 7: Estimated energy requirements for each crew member

A part from the kilo-calories, it is also important that the diet for each crew member includes macro-nutrients in the quantities listed in the table below:

	Rel. amount [%]
Carbohydrates	55
Proteins	15
Fats	30
Sum	**100**

Table 8: Crew member food requirements

The corps that would be available with the biomass process are defined in Table 9. The macro-nutrient contents that each corp would provide are also presented:

Type of Crop	kcal per 100g	Carbohydrated [%]	Proteins [%]	Fat [%]
Soybeans	446	30	36	20
Peanuts	567	16	26	49
Quinoa	368	64	14	6
Oats	389	66	17	7
Sweet potatoe	86	20	1.6	0
Strawberry	33	8	0.7	0.3
Tomato	18	3.9	0.9	0.2
Lettuce	15	2.9	1.4	0.2

Table 9: Macro-nutrient contents in the crops

From the data of tables 8 and 9 a simplified exemplary diet could be defined to be able to quantify the exact amount of food production is needed for the mission. Part of the diet has been retrieved from reference [42], but some changes have been made to adapt it to our mission case. The diet has been set for the highest case of energy requirement to be sure to fulfill the requirement of the four crew members.

	Food m. [g]	kcal	Carb. [g]	Prot. [g]	Fat [g]	H.I.	Biomass [g]
Soybeans	210	935.8	63	75.6	42	0.35	600
Peanuts	50	283	8	13	24	0.22	230
Oats	450	1750.5	297	76.5	31.5	0.5	900
Potatoes	50	43	10	0.8	0	0.2	250
Strawberry	50	16.5	4	0.35	0.15	0.2	250
Total	**810**	**3028.8**	**382**	**166.25**	**97.65**	**-**	**2230**

Table 10: Crew diet

In order to determine the biomass production the reference [30] has used a harvest index, that for each crop which is the ratio of edible mass to produced biomass. For some crops the harvest index could not be found for these conditions, so a low one has been assessed to be conservative (HI = 0.2). This is a daily diet considered for each crew member, and as it can be seen it fulfills the required protein, carbohydrate and fat requirements. So the total required food production for the mission would be:

- Daily food mass per member $= 2230\ g$
- Daily food for the whole crew $= 2230\ g\ \cdot 4 = 8920\ g = 8.92\ kg$
- Food mass for the whole mission $= 8.92 \frac{kg}{day} \cdot 8\ months \cdot \frac{30\ days}{1\ month} = 2140.8\ kg$

In the next section, where the equipment to be used will be analyzed, it will be discussed whether is possible to produce all the required ingredients for the diet, or some food storage will be needed.

In the Biomass production process there are two parameters that will alter the mission requirements: oxygen and water. This is due to the plant growth will produce oxygen and consume water. So an extra amount of water has to be produced in order for the biomass to take place, and an extra amount of oxygen will be provided by the biomass system. The data for the outputs depends on the equipment to be used, and so it will be retrieved for the chosen BPS machinery and described in section 4.2.5.

4.1.4 Power

The power needed in the mission will be set by the equipment selected for the mission. Each one will require a certain amount of power, which will be collected and produced by solar panels.

4.1.5 Parameters validation with *BioSim*

In order to verify and be sure that the calculated requirement parameters are correct and that with those conditions the crew will be survive the whole duration of the mission plus the margin of 2 months, *BioSim* simulator program will be used.

BioSim program is an advanced life support system simulator which have multiple interacting subsystems: crew, environment, food, water, power, and air. From the source code the required inputs can be added to each of the subsystem designing the mission to be analyzed. The program will simulate how these inputs work together and how much time the crew will survive under these conditions.

Therefore this simulator is useful to see if the previously calculated mission parameters about oxygen, water, and food are enough for the crew to carry out the mission. The inputs to be introduced into the program are:

- All the crew member characteristics and their activities.
- The quantity of water required by the crew.
- The quantity of oxygen required by the crew.
- The quantity of food required by the crew.
- The same environment conditions stated for the mission.

Once the mission time has elapsed during the simulation, the outputs of water, oxygen, and food were still over zero. Therefore, the required parameters previously calculated are sufficient to fulfill the mission schedule.

4.2 Mission In-Situ technology

Now the in-situ technology that could be used in order to fulfill the previously determined requirements of the mission can be defined. This will allow us to know how much equipment has to be taken to the Moon and so to start an optimization and simulation process of the mission itself.

4.2.1 Power generation

As it was previously explained in Section 3.6, right now the only viable and existing way to produce energy by using some of the resource that can be found in the Moon is carrying from Earth solar panels. The important features of this equipment are the dimensions, mass, volume and the power generation.

The chosen panel is the polycrystalline solar panel. The discovery of this kind of panel was later than the known mono-crystalline one. Their performance are quite similar, even if the poly-crystalline panel could be slightly less efficient. However it presents some advantages:

- It has a faster heating process
- Its fabrication is faster and cheaper

The final package is presented in the Figure below:

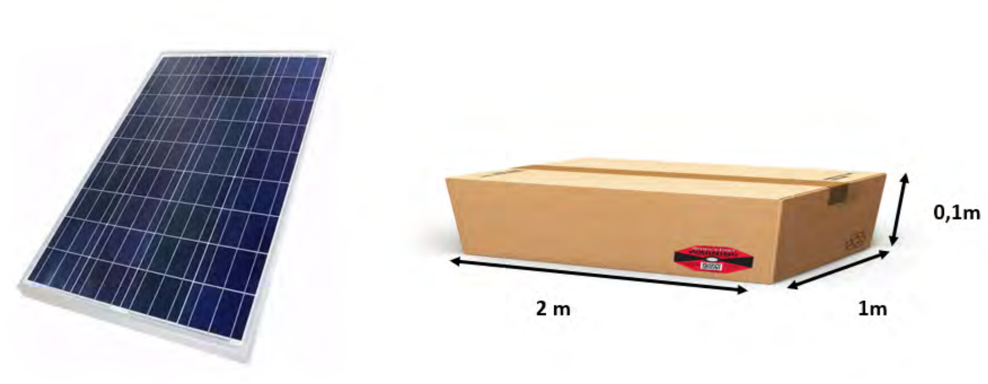


Figure 24: Polycrystalline solar panel of 320W [Google]

The characteristics of such solar panel are now defined Table 11:

Characteristic	**Value**
Real Dimensions	0.99 x 1.956 x 0.05 [m]
Package Dimensions	1 x 2 x 0.1 [m]
Volume Package	0.2 [m^3]
Mass	27 [kg]
Power generation	320 [W]

Table 11: Solar Panel's data

The number of solar panel to carry from Earth will be decided in terms of the total energy required by whole equipment of the mission.

4.2.2 Oxygen production

In this section the equipment that could be potentially used in the Moon to produce oxygen will be analyzed. The chosen candidates are: the Carbothermal Process, PILOT, and ROxygen. After the performance of each one has been examined, the best option for the mission will be selected.

The same information has been extracted from each equipment so to have a valid comparison of the four candidates for the process where the number of equipment of each to be taken to the mission will be assessed. The retrieved data of each equipment is the following:

- Dimensions of real equipment. (Width x Length x Height)
- Dimensions and total volume of the package.
- Total mass of the equipment.
- Batch size of moon-dust that can be stored for the process.

- Amount of oxygen that can be produced and duration time of the process if possible.
- Power required by the equipment to produce oxygen.

All these data has been obtained by reliable documentation. Only for some special cases where the dimensions or the mass could not be find in the documentation, it was retrieved by estimation (taking relation using photographs or some additional useful data). It will be specified for each equipment whenever an estimation has been made. To minimize the possible small mistakes related to the estimations, the size of the packages has been set larger than real equipment to be conservative.

A) Carbothermal process

The carbothermal process equipment can be divided into two different kits: one concerning the actual oxygen production machine; and the other one the solar panel that provide the required energy for the process to function. In the Figure below the packages are presented:

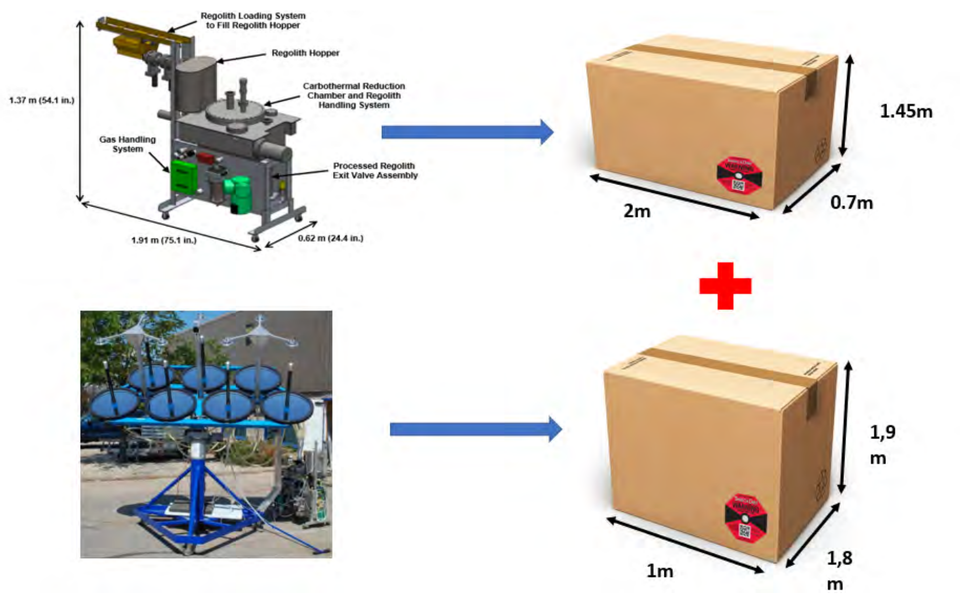


Figure 25: Package dimension of the Carbothermal equipment [12]

Now the data related to the oxygen production is presented. Only the size of the solar panels has been estimated:

Characteristic	Component	Value
Real Dimensions	Machine	0.62 x 1.91 x 1.37 [m]
	Solar Panels	1.72 x 0.92 x 1.8 [m]
Package Dimensions	Machine	0.7 x 2 x 1.45 [m]
	Solar Panels	1.8 x 1 x 1.9 [m]
Volume Package	Machine	2.03 [m^3]
	Solar Panels	3.42 [m^3]
Mass	Machine	600 [kg]
	Solar Panels	510 [kg]
Oxygen Production	-	1 [t/year]
Oxygen Production Percentage	-	9.7% per regolith

Table 12: Carbothermal Equipment's data

Since it already has it own energy feeding system, the Carbothermal process will not be considered when deciding the number of solar panels to be used to supply the mission with the required power.

B) PILOT

The PILOT equipment only consists of one machine. The package dimensions that has been retrieved are presented below:

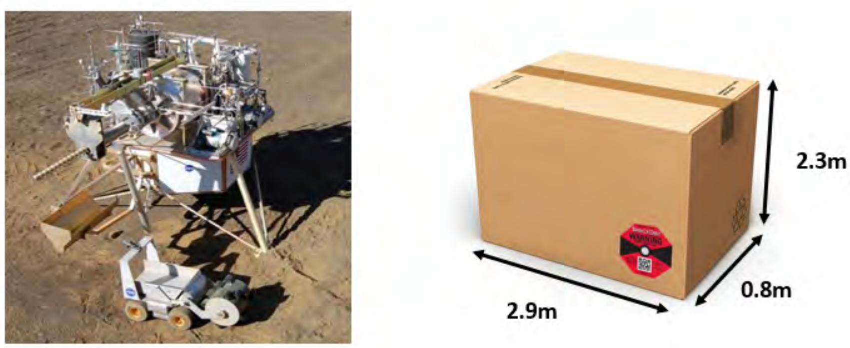


Figure 26: Package dimension of PILOT equipment [4]

Now the data related to the oxygen production is presented in table 13. Only some dimensions of the size machinery have been estimated:

Characteristic	Value
Real Dimensions	0.71 x 2.76 x 2.2 [m]
Package Dimensions	0.8 x 2.9 x 2.3 [m]
Volume Package	5.34 [m^3]
Mass	960 [kg]
Batch Size	15 [Kg]
Oxygen Production	1 [t/year]
Oxygen Production Percentage	150 [gr/batch]
Power Required	5 [kW]

Table 13: PILOT's data

The rover that was used for the test is the Bucket Drum Excavator rover, so it is the one that will be assessed when the transportation rovers will be selected for each equipment.

C) ROxygen

As it can be appreciated in Figure 27 the Roxygen equipment can be divided in three main subsystems: the ramp for the rover to go to the field and collect the moon-dust; the actual oxygen production machine; and the storage subsystem.

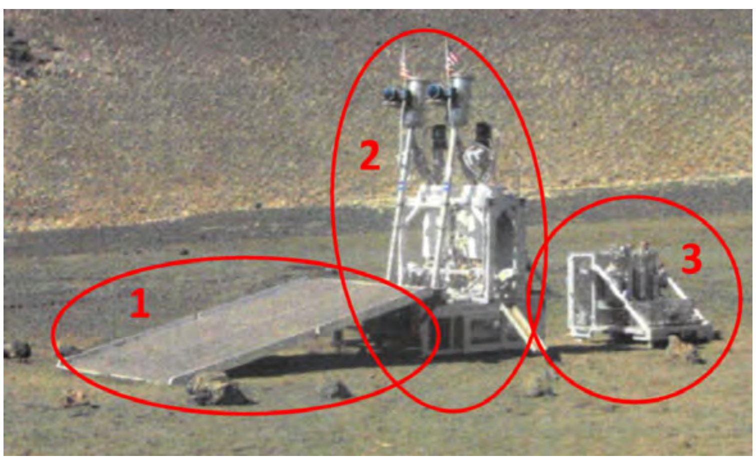


Figure 27: Three components of ROxygen equipment [5]

The final package results is now shown:

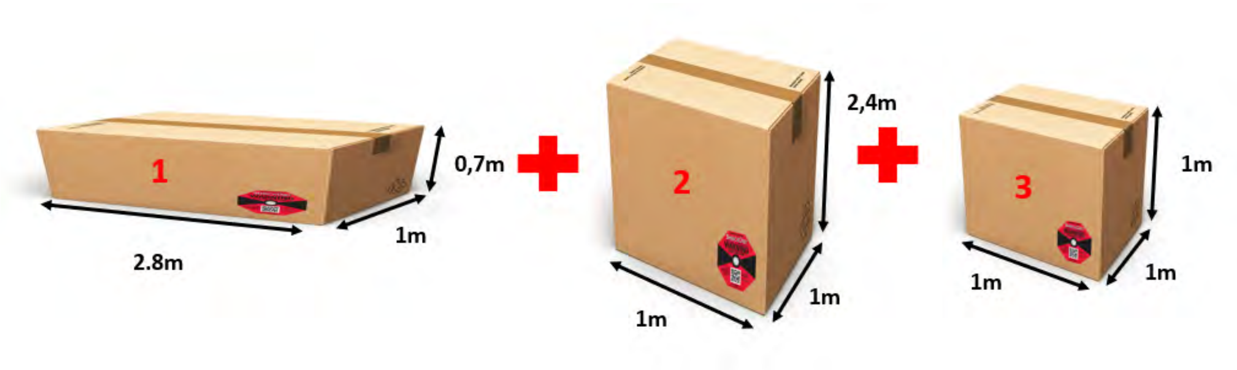


Figure 28: Package dimension of ROxygen equipment [Own Elaboration]

Now the data related to the oxygen production is presented. Only some dimensions of the size machinery have been estimated:

Characteristic	**Component**	**Value**
Real Dimensions	1	0.98 x 2.7 x 0.63 [m]
	2	0.98 x 0.98 x 2.27 [m]
	3	0.98 x 0.88 x 0.94 [m]
Package Dimensions	1	1 x 2.8 x 0.7 [m]
	2	1 x 1 x 2.4 [m]
	3	1 x 1 x 1 [m]
Volume Package	1	1.96 [m^3]
	2	2.4 [m^3]
	3	1 [m^3]
Mass	1	294 [kg]
	2	540 [kg]
	3	225 [kg]
Batch Size	-	10 [kg]
Oxygen Production	-	667 [kg/year]
Oxygen Production Percentage	-	20-50 [gr/batch]
Power Required	-	5 [kW]

Table 14: ROxygen's data

4.2.3 Water production

The previous equipment regarding the production of oxygen should also be able to extract water but during the test fields for each one no valid information about the production has been retrieved. This is why they cannot be considered in the analysis since there is no information about their performance on extracting water.

Therefore the equipment that could be potentially used in the Moon to produce water will be analyzed. The chosen candidates are: the microwave approach, and the Water Recovery System.

The same information has been extracted from each equipment so to have a valid comparison of both candidates for the process where the number of equipment of each to be taken to the mission will be assessed. The known data of each equipment is the following:

- Dimensions of real equipment. (Width x Length x Height)
- Dimensions and total volume of the package.
- Total mass of the equipment.
- Amount of water that can be extracted and duration time of the process if possible.
- Power required by the equipment to produce oxygen.

All these data has been obtained by reliable documentation. Only for some special cases where the dimensions or the mass could not be find in the documentation, it was retrieved by estimation (taking relation using photographs or some additional useful data). It will be specified for each equipment whenever an estimation has been made. To minimize the possible small mistakes related to the estimations the size of the packages has been set larger than real equipment to be conservative.

A) Microwave approach

The equipment of the microwave method for extracting water from lunar regolith can be divided into 4 different packages as it can be observed in Figure 29. Those subsystems are: the microwave; the two machines placed at the floor; and the tube connecting the whole system.

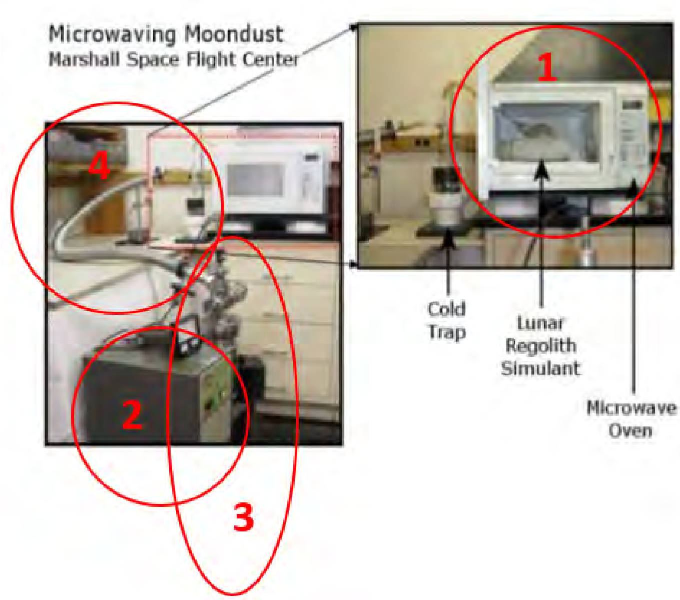


Figure 29: Subdivisions of Microwave approach equipment [18]

The four packages with their dimensions are now shown in Figure 30:

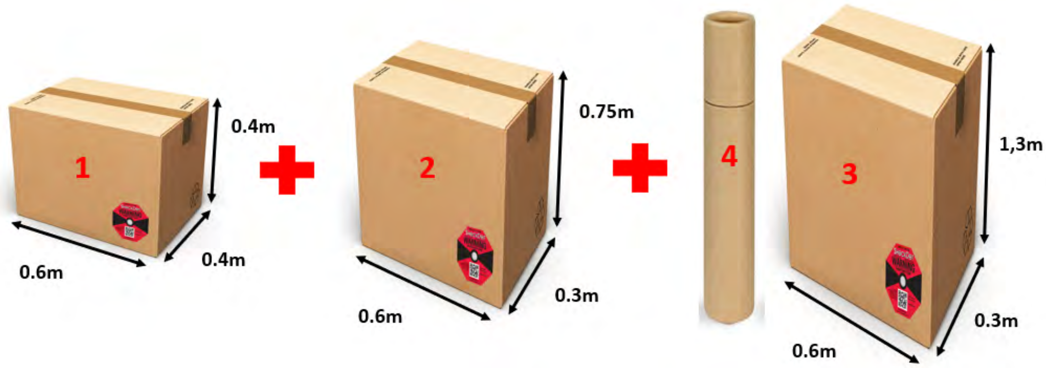


Figure 30: Package dimension of Microwave approach equipment [Own Elaboration]

The data regarding the characteristics and the overall performance of the equipment are the following. For this case some of the dimensions have been estimated:

Characteristics	Component	Value
Real Dimensions	1	0.35 x 0.55 x 0.32 [m]
	2	0.24 x 0.55 x 0.72 [m]
	3	0.24 x 0.55 x 1.20 [m]
	4	1.2 m long with a diameter of 2.4 cm
Package Dimensions	1	0.4 x 0.6 x 0.40 [m] and 0.096 [m^3]
	2	0.3 x 0.6 x 0.75 [m] and 0.135 [m^3]
	3	0.3 x 0.6 x 1.30 [m] and 0.468 [m^3]
	4	1.3 long and 0.026 diameter [m] and $5.428 \cdot 10^{-4}$ [m^3]
Mass	1	15 [kg]
	2	40 [kg]
	3	40 [kg]
	4	2 [kg]
Water Extracted	-	95 % of the water extracted in 2 minutes
Power Required	-	1200W of microwave (Average)

Table 15: Microwave process data

It should be assigned transportation rovers for this equipment so to bring the required regolith to the system.

In the experiment, water (2%) was injected into a lunar regolith simulant (JSC-1). As it is pointed out in the table, in two minutes it is possible to extract 95% of that water. So if considering 1 kg of feedstock per cycle:

- Water extracted per cycle = $0.95 \cdot 0.02 \cdot 1\ kg = 0.019kg$

The process could be repeated around 20 times per hour considering that feedstock should be changed between each process. This process could be carried out just around 2 or 3 hours since the presence of a crew member would necessary. So the total amount of water that this method could produce is:

- Water extracted in 1 hour: $0.019\,kg \cdot 20 = 0.38\,kg$
- Water extracted in a day: $0.38\,kg \cdot 3 = 1.14\,kg$
- Water extracted in the whole mission: $1.14\,\frac{kg}{day} \cdot 8\,month\frac{30days}{1\,month} = 273.6\,kg$

B) Water recovery system

Finally the package for the Water Recovery System has been prepared, as it can be observed in Figure 31:

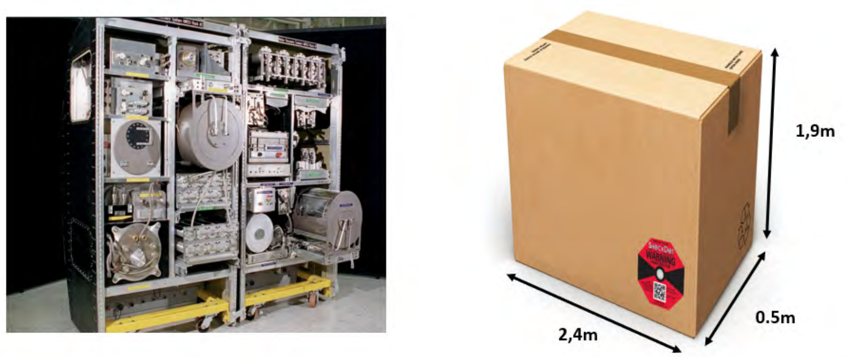


Figure 31: Package dimension of MRS equipment [20]

All the information about its characteristics and performance has been retrieved. Some of the dimensions have been estimated.

Characteristics	Value
Real Dimnensions	0.45 x 2.25 x 1.8 [m]
Package Dimensions and Volume	0.5 x 2.4 x 1.9 [m] and 2.28 [m^3]
Mass	2500 [kg]
Water Produced	12 [l/day]
Power Required	1.7 [kW]

Table 16: Water Recovery System Data

4.2.4 Shelter Construction

Nowadays there exist mainly two different options to build a shelter in the Moon using in-situ resources to supply the crew with an infrastructure that protect them from the harsh lunar environmental conditions. These options are:

- Use the in-situ resources to build the module.

- Dig into the surface to create a cave habitat.

The first one seems to be the best option since compared with excavating the Moon, the amount of material involved in the operation is much less. Also since the Moon geological system is not fully known, the cave habitat should need a further study to be consider a fully valid option.

Nowadays building a shelter with in-situ resources has mainly one feasible approach which is: Use a 3D printer of the scale of the shelter and print out the habitat module in its final dimensions. This approach could be implemented using both methods analyzed in the previous section: D-Shape and Contour Crafting. For this case there would be a main limitation factor: the size of the shelter. It should be a small size so that the 3D printer is able to print the full shelter. In fact nowadays the largest 3D printer that has been used and we have data of is a D-Shape printer that has the dimensions 6x6x3m.

Since any information about either the performance nor characteristics of the Contour Crafting method exist, the D-Shape machine will be the selected one to build a shelter for the mission.

D-shape printer

There already exits a study of the brick approach for a Mars Mission that can be found ind detail in the reference [46]. We could use a similar approach of the study but adapting it to our needs. This study basically states the creation of a combination of modules that would have the organization and form of the Figure below:

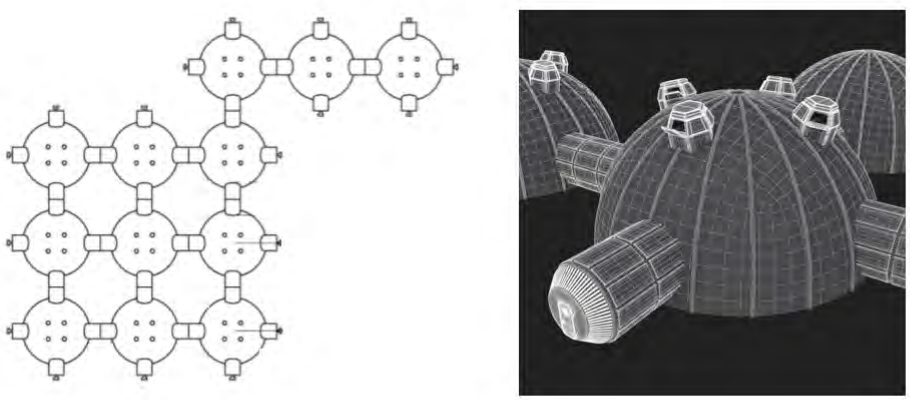


Figure 32: Example of the shelter idea and configuration of the Mars Mission [46]

As previously mentioned the largest printer we have is a 6x6x3m. So the domes should be smaller than that. To build those domes, the printer should have a shield from the lunar environment. In the Mars study they use the following strategy: they print in the landed spacecrafts triangles with a height of 2.4m and then this pieces would be constructed into the large multipurpose 'ag-dome', that would be used as a sort of scaffolding for the 3D printer. Once the printer is shielded, can proceed to print the domes for the crew. The domes would be also connected between them through connection units:

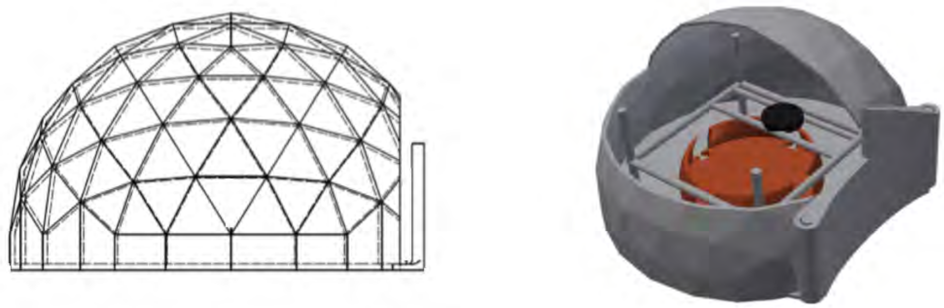


Figure 33: 'Ag-dome' structure formed by triangles to shield the 3D printer [46]

Th D-Shape printer capable of doing so, would be and have the characteristic enumerated below:

Characteristics	**Value**
Printer size	6x6x3 $[m^3]$
Print volume	5x5x2.5 $[m^3]$
Weight (without powder)	1300 $[kg]$
Total Weight	5000 $[kg]$
Structure	Aluminum gantry
Layer thickness	5-10 $[mm]$
Printing speed	1.2 $m^3/hour$ at 10 mm layers

Table 17: D-Shape printer's data

So the package dimension for the mission would be the one of Figure 34.

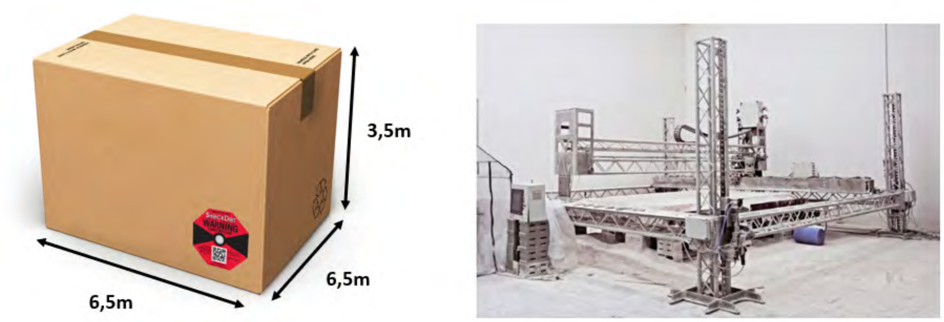


Figure 34: Package dimensions of the required D-Shape 3D printer [Google]

To seek of simplicity a few assumptions about the printer are made:

- The 3D printer is considered to be carried to the Moon already assembled, as the package shows. Even though it is assumed to resist the rocket launch.
- A number of rovers will be assessed to the 3D printer to help with the transportation of the feedstock and the removal of it when the structures is completed.

- No further analysis about the whole printing process after the 3D printer has successfully landed on the Moon will be performed, since it is out of the scope of the research.

4.2.5 Food production

In order to run the simulation for the mission, the main important aspects to take into account for the biomass production system are:

- Growth area available: It is the place where the crops can be planted. It will crucial for the sizing and selection of number of shelters to be built.
- Illumination: The crops to be planted need light so they can grow. This light can be provided naturally or artificially.
- Air balance: The air in the cabins where Biomass Production System is activated, must always have the same balanced composition.

The best option would be to use the natural light provided by the location conditions. However, to be conservative and in terms of the available technology we will assume all light coming from artificial sources. This light will be powered energy generated by solar panels.

The environment in which the Biomass Production System will be placed, will be altered by the plant growth process. In fact the plants will produce oxygen and consume CO_2. So it is important to maintain a balance in the environment. It could be achieved in two ways:

- The environment could be balanced naturally if the crew quarters and the crop quarter are connected since the crop and crew processes are opposite.
- The crop environment is isolated, and the balance will be achieved artificially by oxygen and CO_2 reservoir units.

Lunar Greenhouse (LGH)

Right now, the only equipment that could fulfill the previous requirements and that could be almost a closed-loop system would be the Prototype Lunar Greenhouse. In fact its performance will depend on the interaction of several actors. For instance fertilizer, water and CO2 are added, to keep the atmosphere and soil regulated.

Another important thing is that the crops are not grown on even ground within the tube, therefore the total growth rate have been reported in terms of volume. An estimation could be eventually calculated in order to get the values in terms of growth area and be able to establish the outputs. The main important parameters of the performance of the LGH are presented in the table below. This data is considered for a complex of three LGH tubes.

Type	Daily Amount (per crew member)
Produced biomass	3.39 kg
Condensated water	32.10 kg
Produced O2	0.24 kg
Consumed fertilizer	0.11 kg
Poured water	38.55 kg
Consumed energy	10 kW (average)
Consumed CO2	0.33 kg
Required labor	36 min

Table 18: Inputs and Outputs of Prototype Lunar Greenhouse

As it can be seen in the table above, the prototype greenhouse requires a daily human labor time, which is inside the exercise time of the crew's activity. The illumination is also an important matter since it will be required a lot of energy. The lighting cycles would consists of 17h of light followed by 10h of darkness.

The package configuration for the Prototype Lunar Greehouse is presented in the next Figure:

Figure 35: Package of the LGH [27]

The size, mass, and other characteristics of one LGH tube are now enumerated in the table below:

Characteristic	Value
Real Dimensions	Diameter = 2.5 [m]
	Length = 11.5 [m]
Package Dimensions	2.6 x 11.6 x 2.6 [m]
Volume Package	78.42 [m^3]
Mass	2000 [kg]
Growth Volume	36.8 [m^3]

Table 19: Lunar Greenhouse's data

Probably it should be taken to the Moon before the mission so to have time for the plant to grow.

As it was previously mentioned in the parameter definition of section 4.1.3, the process will produce oxygen and consume water. Here are the input and output data of the LGH per complex performance (3 capsules). First the oxygen output:

- Oxygen produced in a day by BPS = 0.96 kg/day
- Oxygen produced in the whole mission by BPS = $0.96\frac{kg}{day} \cdot 8\ month \cdot \frac{30\ days}{1\ month} = 230.4\ kg$

Now the water input and output:

- INPUT:
  - Condensed water produced in a day by BPS = 128.4 kg/day
  - Condensed water produced in the whole mission by BPS = $0.96\frac{kg}{day} \cdot 8\ month \cdot \frac{30\ days}{1\ month} =$ 30816 kg
- OUTPUT:
  - Required water in a day by BPS = 154.2 kg/day
  - Required water in the whole mission by BPS = $154.2\frac{kg}{day} \cdot 8\ month \cdot \frac{30\ days}{1\ month} = 37008\ kg$
- OVERALL:
  - Required water in a day by BPS = 154.2 kg/day - 128.4 kg/day = 25.8 kg/day
  - Required water in the whole mission by BPS = $25.8\frac{kg}{day} \cdot 8\ month \cdot \frac{30\ days}{1\ month} = 6192\ kg$

Finally the food that will be produced per complex in the LGH:

- Food produced in a day by BPS = 9.04 kg/day
- Food produced in the whole mission by BPS = $9.04\frac{kg}{day} \cdot 8\ month \cdot \frac{30\ days}{1\ month} = 2169.6\ kg$

4.2.6 Transport rovers

A transport rover will be assigned to each equipment that needs a batch of moon-dust. The selected ones are the NASA RASSOR and the Bucket Drum Excavator.

NASA RASSOR

This is the best transport rover in terms of performance, since it can transport but also dig in much more depth than other equipments. For this reason it will be the one to be assigned unless a specific equipment has used another kind of rover during the field tests:

Figure 36: Package dimensions of the NASA RASSOR rover [38]

The detailed information about its characteristics and performance is now presented:

Characteristics	Value
Real Dimensions	0.43 x 0.88 x 0.85 [m]
Package Dimensions	0.7 x 2 x 0.4 [m]
Package Volume	0.56 [m^3]
Mass	50 [kg]
Mining Rate	10 [min]
Feedstock Capacity	20 [kg]

Table 20: NASA RASSOR Data

Bucket Drum Excavator

The Bucket Drum Excavator will be use specifically for the equipment that used it in the field tests, such as PILOT. In fact, the tests proved that the performance results obtained are achievable using this transportation rover.

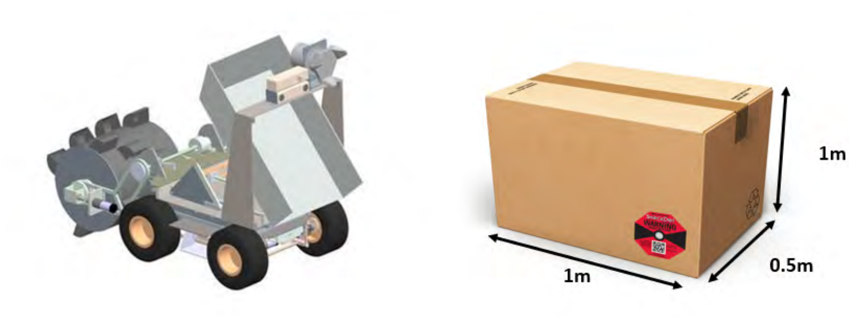


Figure 37: Package dimensions of the Bucket Drum Excavator rover [4]

The detailed information about its characteristics and performance is now presented:

Characteristics	Value
Real Dimensions	0.43 x 0.88 x 0.85 [m]
Package Dimensions	0.5 x 1 x 1 [m]
Package Volume	0.5 [m^3]
Mass	80 [kg]
Transport Rate	50 [kg/h]
Feedstock Capacity	18 [kg] (Dump Bed)
	10 [kg] (Drum Load)

Table 21: Bucket Drum Excavator Data

The Bucket Drum Excavator will be assessed just to the equipment that for which the feedstock collection or transportation in the test results have been carried out by this rover.

4.2.7 Storage equipment

It would be appropriate to assess some storage to those equipments that is producing or extracting oxygen and water from the surface of the Moon. Doing so, the produced oxygen or water can be store and then taken to the Moon-base.

Oxygen Storage

The oxygen storage is presented in the Figure below, with the final package dimensions too.

Figure 38: Oxygen tank dimension's package [47]

The tank is able to store up to 7.5 kg of oxygen and has an empty mass of 7.5 kg. This oxygen storage would not be considered for the ROxygen case since it already has a storage compartment in its equipment.

Water Storage

The water storage is presented in the Figure below, with the final package dimensions too.

Figure 39: Water tank dimension's package [48]

Each tank has a mass of 0.5 kg and is able to store up to 3.2 kg of water. The water containers will only be taken to the Moon for the Microwave approach for the extraction of water.

4.2.8 Equipment Summary

The following table will be presented to sum up the different equipment choices we have, showing the three main characteristics to take into consideration for the mission: volume, mass and power consumed.

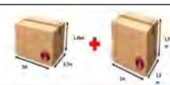
	Equipment	Package	Volume [m^3]	Masa [kg]	Power [kW]
	ROXYGEN		5.36	1059	5
	CARBOTHERMAL		5.45	1110	-
	PILOT		5.34	960	5
	MICROWAVE		0.700	97	2.4
	WRS		2.280	2500	1.7
	LGH		78.420	2000	10
	D-SHAPE		147.880	1300	2
	BUCKET		0.500	80	-
	RASSOR		0.560	50	-
	OXYGEN TANK		0.067	7.50	-
	WATER TANK		2.420	0.50	-

Figure 40: Summary table of the equipment for the mission [Own Elaboration]

The only selection process is for the oxygen and water production system. For the case of the oxygen, there are three different possibilities. All of them present similar values of volume and mass, so the discriminant parameters will be the power consumption and their performance. The ROxygen equipment will be discarded since is the one that produces less amount of oxygen, therefore more equipment should shipped, increasing the required mass and volume. PILOT and Carbothermal equipments show the same performance, producing both 1000 kg of O_2 per year. The differentiating parameter is the power. The power needed for the carbothermal process is already included in its system, and so in its mass and volume values. So the PILOT would need an extra amount of weight and volume adding some solar panel to provide it with the needed energy. So it can be concluded that the best option for producing oxygen is the Carbothermal equipment, and it will be the chosen one to be used in the mission if required.

For the case of the water production, both methods can be used simultaneously. Even if in terms of performance the WRS seems to be the most efficient one, it depends on a particular input which is the liquid waste produced by the crew. So the input is limited and could be enough to fulfill the crew requirements but not any extra water requirement. This is why in case of any other water demand, the microwave approach could be used to cover it.

4.3 Mission Options

In this subsection, the feasibility of a mission in the Moon using in-situ resources will be analyzed. To do so, it is would be interesting to compare it with an opposite mission that is focused on carrying the required material from the Earth, to have a reference point.

Now different mission approaches will be considered and studied. The parameters to be compared in this analysis are the production of oxygen, water, food and power.

Dependence on Earth

This would be an Earth dependent mission to the Moon. Each required parameter to guarantee the crew survival for the 8 months would be carried from Earth. This approach is the opposite one that this report aims to do but it will be used just as a reference to see if nowadays the utilization of in-situ resources technologies to produce during the mission is feasible.

Mission Option 1

To determine the parameters is just necessary to enumerate the different mass crew requirements of oxygen, water, food and power:

	Oxygen [kg]	**Water [kg]**	**Food [kg]**	**Power [kW]**
Required Quantity	1000	2324	2140.8	-

Table 22: Required quantities of O, H_2O and Food for the whole mission

Since we only have mass reference of what the crew needs, it is now time to make it physical and determine the volume that is required to carry everything to the Moon. To do so the previously described water and oxygen storage equipment will be used for this purpose:

	Oxygen [kg]	Water [kg]
Required	1000	2320
Storage Capacity	7.5	3.2
Total Number	**134**	**725**

Table 23: Total required number of containers required

In order to determine the storage quantity and volume needed for the food, the following approach could be used:

- A package for each meal could be created.
- The dimensions would be 0.34 x 0.24 x 0.1 [m] (Width x Length x Height). These dimensions are similar to the one that can be found in an airplane.
- Since there are three meal along the day, the food mass needed by each crew member will be divided by three to get the mass for each meal.
- To be conservative, a 10% will be added to the mass and volume for the final package.

The next table presents the data obtained for the food packaging for a meal of one crew member:

	Mass [kg]	Meal Mass[kg]	Meal Vol. [m^3]	P. Vol. [m^3]	P. Mass [kg]
Peanuts	0.23	0.077	-	-	0.25
Oats	0.90	0.300	-	-	0.99
Soybeans	0.60	0.200	-	-	0.66
Potatoes	0.25	0.083	-	-	0.275
Strawberries	0.25	0.083	-	-	0.275
Total	**2.23**	**0.743**	**0.00816**	**0.00898**	**0.817**

Table 24: Package Volume and Mass for each Meal

For the whole mission a total number of 2880 of the packages described above should be shipped to fulfill the food requirement of the whole crew of 2140.8 kg.

Finally only one 3D printer would be enough to build the shelters for the crew. However it should need rover to collect the regolith to be used as powder by the machine. From reference [45], it is said that a total of 1500 kg of robotic rovers would be required. This number would mean a total of 30 NASA RASSOR rovers to fulfill the 3D printer requirements.

The following table is presented to sum up the required equipment to be carried to the Moon for the mission:

	Volume [m3]	Mass [kg]	N [-]	Power [kW]
OXYGEN	0.067	7.5 + 7.5	134	-
WATER	2.42	3.2 + 0.5	725	-
FOOD	0.009	0.817	2880	-
3D PRINTER	147.875	1300	1	2
ROVER	0.56	50	30	-
Total	**1954.07**	**9845.46**		**2**

Table 25: Total equipment and Power required for Mission 1

As it can be seen the total power required by the whole equipment is 2 kW. One solar panel covers 320 W. So a total of 7 panels would be needed for the system to work.

2) In-Situ Resource Utilization

In the case of producing everything in-situ using the resources of the Moon, there would be two different approaches since there are some interactions between the equipment. In fact when producing food with the orchard there would be the secondary effect of consuming water and producing oxygen. This is not profitable since more oxygen than need would be produced, having a surplus of oxygen.

Two possible mission approaches to face this issue could be follow:

- Having a higher growth area to produce food and so to produce also the required oxygen to not need the oxygen production equipment.
- Reducing the oxygen production equipment to level the oxygen production together with the biomass production system.

To better see which one could be the best option, the two different mission options will be created.

Mission Option 2

Increasing the plant growth area will produce more oxygen for the crew but at the same time more water will be needed to make it possible. So it has an advantage and a disadvantage. If the required 1000 kg of oxygen have to be produced by the Biomass Production System, four complexes of LGH have to be used. This system will produce and consume the following inputs and outputs for the whole duration of the mission (8 months):

		Oxygen [kg]	Water [kg]	Food [kg]
Produced Quantity	Human Met.	-	-2324	-
	Secondary	2500 x 4	-6192 x 4	2169.6 x 4
	Total	**1000**	**-27092**	**8678.4**

Table 26: Produced quantities of O_2, H_2O and Food to fulfill requirements

As it can be seen the amount of food produced would largely exceed the minimum required, so there would be a surplus of food. But the growth is no restricted to be used only for food purposes.

In fact we could cover the crops are to produce the food requirements and the other available area normal plants could be used only for the production of oxygen.

The amount of water would rise considerably, and a total of 27092 kg of water should be produced to fulfill the needs of the crew and the biomass system. Part of the water (the one concerning the crew needs) would be produced by the WRS which produces 12 kg of water per day and largely covers the crew needs. The microwave approach could be used to produce the water required by the biomass system. The water to be produced in the whole mission is 24768 kg, which would be around 103.2 kg per day. Since this method only produces 1.14 kg per day, around 91 equipments would be required to produce it. Of course a NASA RASSOR would be assessed to each equipment so to collect and dig the required amount of regolith to cover the process.

It would be also needed to determine the amount of tanks that should be carried from Earth to use as storage for the whole duration of the mission. For the case of oxygen, the following reasoning could be done:

Since the total amount of produced oxygen is 1000 kg, then a total of 134 tanks should be enough to fulfill the mission requirements (7.5 kg capacity). This number is too high but a strategy to maximize its usage and minimize volume and mass for the mission could be implemented. Since the crew consumes less amount of oxygen than is produced, and the biomass system would produce around 4.2 kg of oxygen per day, which is exactly what the whole crew consumes in a day. Therefore, since the crew would collect once a week the water tanks replacing them for new empty ones, it would be just necessary to bring at least oxygen storage for two weeks. A safety margin in case of some possible issue could be implemented.

- Produced oxygen in 4 weeks $= 4\,weeks \cdot \frac{7\,days}{1\,week} \cdot 4.2\,kg = 117.6\,kg$
- Oxygen tanks needed $= 117.7\,kg/7.5\,kg = 15.69 \approx 16$

Regarding the water production, a total of 8467 tanks would be enough to fulfill the mission requirements. This number is extremely high, so it should be reduced considering that the water is taken out of the tank the container will be empty and with no usage. So to maximize its usage and minimize volume and mass for the mission similar strategy done for the oxygen containers is implemented. The crew basically consumes the same amount of water that is produced, since the 91 equipments would produce 103.2 kg of water per day which is the needed one to be consumed in a day. Therefore, since the crew would collect once a week the water tanks replacing them for new empty ones, it would be just necessary to bring at least water tank for two weeks. A safety margin in case of some possible issue could be implemented, and increase the supply to a number able to cover 4 weeks.

- Produced water in 4 weeks $= 4\,weeks \cdot \frac{7\,days}{1\,week} \cdot 103.2\,kg = 2889.6kg$
- Water tanks needed $= 2889.6\,kg/3.2\,kg = 903$

Finally only one 3D printer would be enough to build the shelters for the crew. However it should need rover to collect the regolith to be used as powder by the machine. Again, taking from reference [45], a total of 30 NASA RASSOR rovers to fulfill the 3D printer requirements.

	Equipment	Volume [m3]	Mass [kg]	N	Power [kW]
OXYGEN	-	-	-	-	-
WATER	Microwave	0.7	97	91	2.4 x 91
	WRS	2.28	2500	1	1.7
	Tanks	2.42	0.5	903	-
	Rovers	0.56	50	91	-
FOOD	LGH	78.42	2000	4	10 x 4
3D PRINTER	D-Shape	147.88	1300	1	2
	Rovers	0.56	50	30	-
Total		**27128.5**	**5100.3**		**262.1**

Table 27: Total equipment and Power required for Mission 2

As it can be seen the total power required by the whole equipment is 262.1 kW. One solar panel covers 320 W. So a total of 820 panels would be needed for the system to work.

Mission Option 3

The last mission option would require compensation between the oxygen production system and the biomass production system. To do so, the oxygen that is produced by the minimum plant growth area to produce the required food to feed the crew, will be subtracted to the needed oxygen. The overall needed parameters are:

		Oxygen [kg]	Water [kg]	Food [kg]
Required Quantity	Human Met.	1000	-2324	0
	Secondary	-230	- 6192	2169.6
	Total	**770**	**-7632**	**2169.6**

Table 28: Production quantities of O_2, H_2O and Food to fulfill requirements

To be able to produce those requirements the needed equipment will be now described and analyzed.

For the production of oxygen two Carbothermal equipments would be required, since the production for one in 8 months would be around 670 kg, which is not enough to fulfill the required 770 kg. Moreover a number of tanks would be needed to store the oxygen. Since the total amount of produced oxygen is 1340 kg, then a total of 179 tanks should be enough to fulfill the mission requirements (7.5 kg capacity). The number of required containers is too high, so the same strategy executed for mission 2 can be used to maximize its usage and minimize volume and mass for the mission. The crew consumes less amount of oxygen than is produced, since she equipments would produce around 5.6 kg of oxygen per day the whole crew consumes 4.2 kg of oxygen per day. Therefore, since the crew would collect once a week the water tanks replacing them for new empty ones, it would be just necessary to bring at least oxygen storage for two weeks. A safety margin in case of some possible issue could be implemented.

- Produced oxygen in 4 weeks $= 4\,weeks \cdot \frac{7\,days}{1\,week} \cdot 5.6\,kg = 156.8\,kg$
- Oxygen tanks needed $= 156.8\,kg/7.5\,kg = 20.91 \approx 21$

One NASA RASSOR would be assessed to each Carbothermal equipment so to extract the required amount of moon-dust for the process.

Regarding the water production, the number of WRS to cover the needs of the crew would be one. This equipment would produce around 12 kg of water per day. The daily required amount is 8.48 kg, so it largely covers the requirement. For the needed water for the biomass process, the microwave approach could be used. The required water is 25.8 kg per day. The production of one microwave equipment would be around 1.14 kg. So a total of 23 microwaves would be needed.

Each microwave would be assessed with one NASA RASSOR rover to dig and collect the required regolith from the lunar surface. This water should be stored and then transport to the biomass quarters.

A total of 1935 tanks should be enough to fulfill the mission requirements. Similarly to the previous cases this number could reduce since once the water is taken out of the tank the container will be empty and with no usage. The crew basically consumes the same amount of water that is produced, since the 23 equipments would produce 26.2 kg of water per day for 25.8 kg to be consumed in a day. Therefore, since the crew would collect once a week the water tanks replacing them for new empty ones, it would be just necessary to bring at least water tank for two weeks. A safety margin in case of some possible issue could be implemented, and increase the supply to a number able to cover 4 weeks.

- Produced water in 4 weeks $= 4\, weeks \cdot \frac{7\, days}{1\, week} \cdot 26.2\, kg = 734.2$
- Water tanks needed $= 734.2\, kg/3.2\, kg = 229.4 \approx 230$

Regarding the Biomass production system a complex of three LGH tubes would be required to produce the food for the crew during the whole mission.

Finally only one 3D printer would be enough to build the shelters for the crew. The same previously made reasonings in terms of the building of shelters will be considered.

The next table is presented to sum up the total equipment that would be required for the whole mission:

	Equipment	Volume [m3]	Mass [kg]	N	Power [kW]
OXYGEN	Carbothermal	5.45	1110	2	-
	Tanks	0.067	7.5	16	-
	Rovers	0.56	50	2	-
WATER	Microwave	0.7	97	23	2.4x23
	WRS	2.28	2500	1	1.7
	Tanks	2.42	0.5	230	-
	Rovers	0.45	50	23	-
FOOD	LGH	78.42	2000	1	10
3D PRINTER	D-Shape	147.88	1300	1	2
	Rovers	0.56	50	30	-
Total		**841.5**	**13236.0**		**68.9**

Table 29: Total equipment and Power required for Mission 3

As it can be seen the total power required by the whole equipment is 68.9 kW. One solar panel covers 320 W. So a total of 216 panel would be needed for the system to work.

4.4 Mission Overview

Now an overview of the three mission options is presented in the table below, by comparing the number of equipment necessary to complete each mission.

		MISSION 1	**MISSION 2**	**MISSION 3**
CREW	Members	4	4	4
OXYGEN	Carbothermal	0	0	2
	Tanks	134	0	16
WATER	Microwave	0	91	23
	WRS	0	1	1
	Tanks	725	903	230
FOOD	LGH	0	4	1
	Storage	2880	0	0
3D PRINTERS	D-Shape	1	1	1
ROVERS	NASA RASSOR	30	121	55
SOLAR PANELS	Panels	7	820	216

Table 30: Summary comparison between the three mission options

A comparison between the total volume and mass required for each mission would be interesting:

	MISSION 1	**MISSION 2**	**MISSION 3**
Volume [m^3]	1954.1	27128.5	841.5
Mass [kg]	9845.5	5100.3	1323.0

Table 31: Total mass and volume of the equipment for each mission

5 Optimization problem

In this section the simulation of the three mission options previously described will be carried out. The main goal is to get the optimized results of each mission, so to be able to have a reliable comparison. To do so a specific software called *SpaceNet* will be used. This program is an integrated interplanetary supply chain management and logistics planning and simulation software tool, that will be used to design the whole mission.

In the software the launch, transportation and landing stages should be defined, in order to design the mission. At it was mentioned in section 4.1, the landing site in the Moon will be the South Pole due to its favorable conditions. This location can be seen in Figure 41, where the other nodes are also presented.

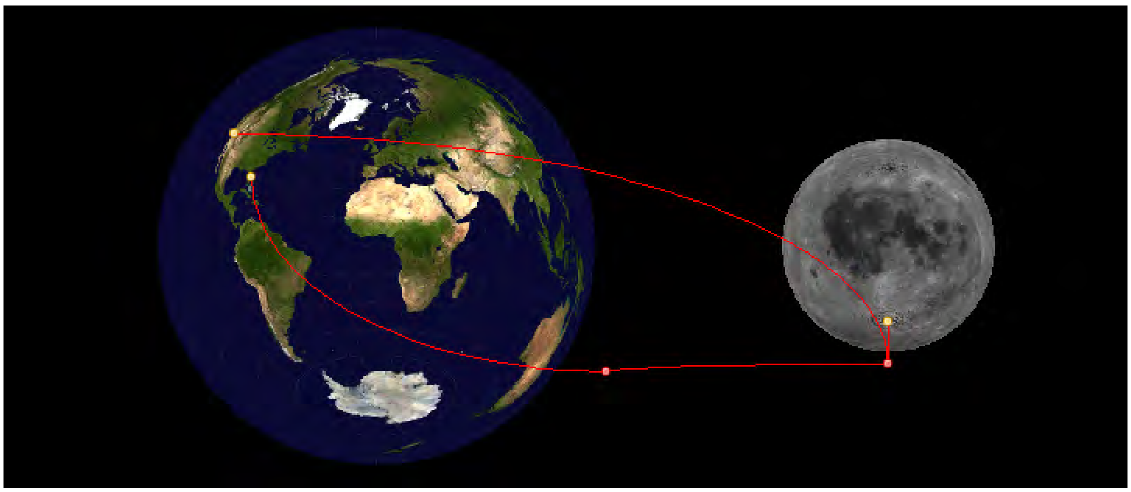


Figure 41: Earth-Moon system SpaceNet visualization [*SpaceNet*]

The red line placed at the bottom is the one of our interest, since it will be the path of the launchers that will be sent to the Moon. As it can be observed the trajectory can be divided into three different stages:

- The launch will be executed at the KSC node (Kennedy Space Center), in Florida, USA.
- The first stage is getting the vehicles from KSC to LEO (Low Earth Orbit), and so letting them into orbit.
- The second stage consists of passing from LEO to LLPO, which is the Low Lunar Polar Orbit.
- Finally, the last stage is the descent from LLPO to the lunar surface.
- After that the crew should stay in a mission for 6 months in the Moon.

The space transport that is presented in the different stages are implemented with the launchers specified by the program, which are two: Ares I (used to transport the crew), and Ares V (used to transport the payload). Both rockets will be launched separately but they will cover the same trajectory and stages previously described. Even though each rocket will have different burning stages since composed differently. To have a better understanding of these two rockets, their structure and stage performance will be now analyzed.

The main elements and stages considered by SpaceNet for the Ares I rocket are:

- Ares I First Stage: it is a propulsive vehicle and the first to be burnt after launch.
- Ares I Upper Stage: it is a propulsive vehicle and the second to be burnt First Stage does.
- Orion Crew Module and Orion Service Module: These are the modules to land on the lunar surface and that guarantee the survival of the crew along the trip.

These elements can be seen in Figure 42 where the exploded view of the Ares I rocket is shown.

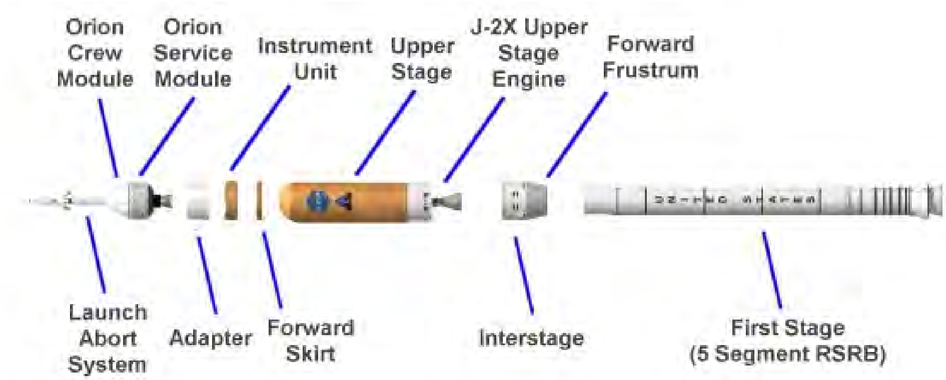


Figure 42: Exploded view of Ares I rocket [53]

On the other hand, the main elements and stages considered for the Ares V rocket are:

- Ares V SRB: It is the first propulsive vehicle to be burn after launch.
- Ares V Core: It is the second propulsive vehicle that is burnt after the SRB.
- EDS: It is the Earth Departure Stage. It is also a propulsive vehicle. It is intended to boost the rocket's payload LEO and from there send the payload out of that orbit to its destination.
- Lunar Surface Access Module: It is an lunar excursion module which is intended to land on the Moon.

These elements can be seen in Figure 42 where the exploded view of the Ares V rocket is shown.

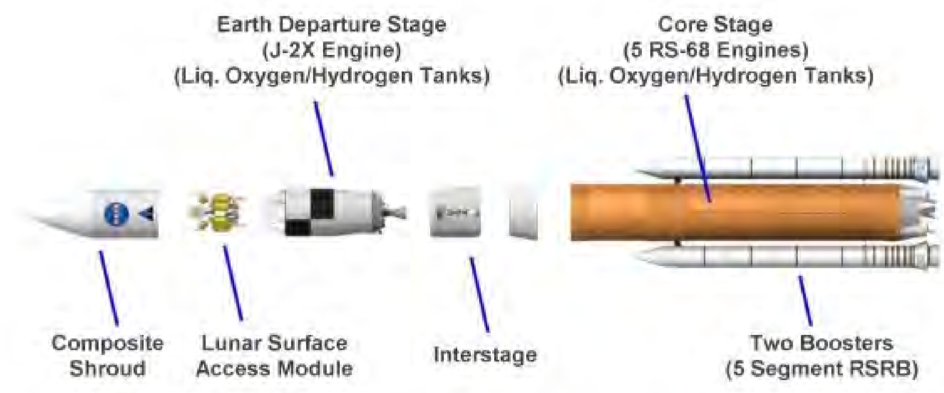


Figure 43: Exploded view of Ares V rocket [53]

The main two modules or elements of the rockets of our interest are the Orion CM of Ares I and the Lunar Surface Access Module of Ares V, which are the two modules that we will use to introduce the needed crew and equipment for the mission. These modules are important since they are the ones that will set the limit in size and mass that can be carried out to the Moon for each launch. The image below give us a closer look of how the crew would be arranged into the Orion CM of Ares I.

Figure 44: Example of the crew module to be used in the mission [Google]

The election of the module that would descend to the lunar surface will be taking into consideration the fairing size of the Ares V. In fact it should exploit its dimension limits to be able of taking as much payload as possible in one single launch. The Figure below shows the fairing capacity of the Ares V in its extended mission version that offers more space for cargo.

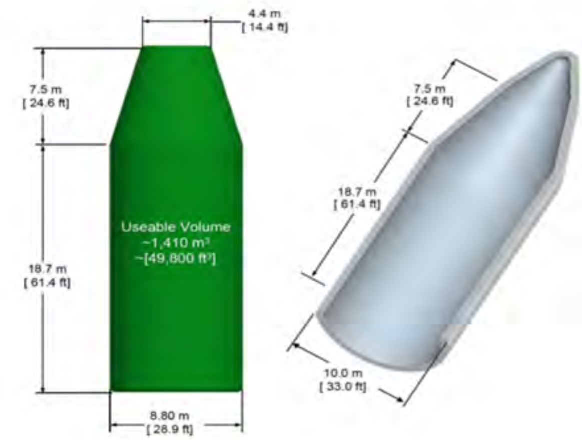


Figure 45: Payload fairing capacity of Ares V rocket [53]

The lunar surface access module chosen for the mission is The MARTA Project (which stands for Moon-based Advanced Reusable Transportation Architecture). It is a lunar surface transportation module capable of sending both astronauts and large masses of cargo to the Moon and back. It consist of a propulsive system placed on the bottom of the structure, and a payload compartment just above it. It can store up to 60 t of cargo in its official dimensions. Since its size exceeds the available volume of the fairing, the dimensions has been reduced and readjusted to fit in Ares V. Therefore its payload mass and volume limits had to be recalculated. Figure 46 shows the result of those calculations.

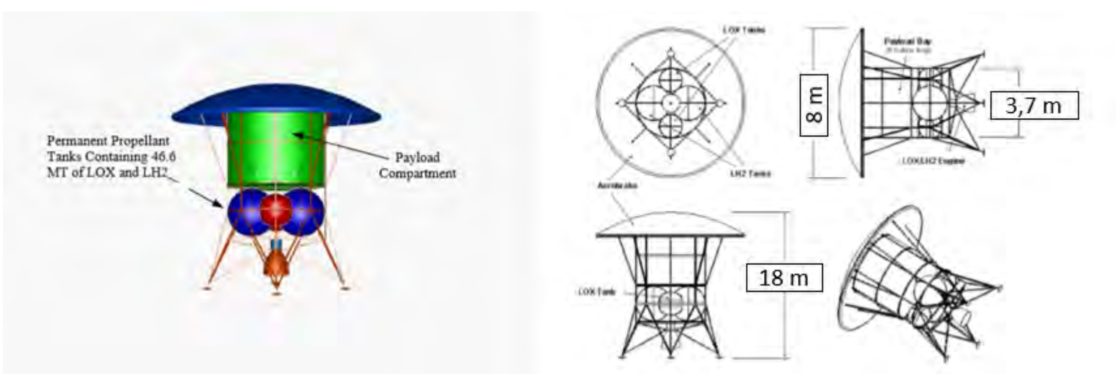


Figure 46: View of the the MARTA Project transfer vehicle [54]

Therefore the new cargo mass and volume limits have been retrieved, giving:

- Available payload volume = 96.77 m^3
- Maximum payload mass = 30 t

Finally, once the trajectory, the launchers size and mass limitations, and the launch sequence have been identified, our data can be introduced into the program. The equipment is defined in terms of mass and volume that has been retrieved in the previous sections. The optimization option will be activated for each mission, in order to have the best combination of equipment transportation.

In other words, to have the lowest possible number of launches for each option, with the previously obtained inputs.

5.1 Results of mission options

<u>Mission 1</u>

The results for the first mission option, consisting on carrying all the requirements from Earth will be presented. From SpaceNet outputs the following results have been obtained for mission option 1:

Launch Type	Launcher Type	Cargo Type	Repetitions
1	Ares I	Crew	1
2	Ares V	Water	18
3	Ares V	3D Printer	1
4	Ares V	3D printer	1
		Panels	
		Rovers	
		Food	
5	Ares V	Water	1
		Oxygen	
TOTAL			**22**

Table 32: Total Launches for mission 1

As it can be seen from the table the main contribution to such a high number of launches are the water tanks. The amount of water is very high, and bringing it to from Earth would not be likely since 18 out of 22 launches are exclusively for water requirements. Only with one WRS the required water for the mission would be produced and the number of launches would be largely reduced. It is a plausible option, since nowadays the WRS is widely used for space mission, and even for this kind of option where everything is carried from Earth it would be used. In fact the water tanks strategy is not a realistic option. Therefore with this reduction the total launches outlook would remain like shown in table 33.

Launch Type	Launcher Type	Cargo Type	Repetitions
1	Ares I	Crew	1
2	Ares V	3D Printer	1
3	Ares V	3D printer	1
		Panels	
		Rovers	
		Food	
4	Ares V	Water	1
		Oxygen	
TOTAL			**4**

Table 33: Optimized total launches of mission 1

The total number of launches has been notably reduced from 22 to 4.

Mission 2

Now the results of the second mission option, consisting on being independent on Earth and biomass dependent. From SpaceNet outputs the following results have been obtained for mission option 2:

<table>
<tr><th>Launch Type</th><th>Launcher Type</th><th>Cargo Type</th><th>Repetitions</th></tr>
<tr><td>1</td><td>Ares I</td><td>Crew</td><td>1</td></tr>
<tr><td>2</td><td>Ares V</td><td>Water</td><td>23</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Ares V</td><td>Biomass</td><td rowspan="2">9</td></tr>
<tr><td>Panels</td></tr>
<tr><td rowspan="3">4</td><td rowspan="3">Ares V</td><td>Biomass</td><td rowspan="3">1</td></tr>
<tr><td>Panels</td></tr>
<tr><td>Rovers</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">Ares V</td><td>3D printer</td><td rowspan="2">1</td></tr>
<tr><td>Rovers</td></tr>
<tr><td>6</td><td>Ares V</td><td>3D printer</td><td>1</td></tr>
<tr><td rowspan="4">7</td><td rowspan="4">Ares V</td><td>WRS</td><td rowspan="4">1</td></tr>
<tr><td>Microwave</td></tr>
<tr><td>Water</td></tr>
<tr><td>Rover</td></tr>
<tr><td>TOTAL</td><td colspan="2"></td><td>37</td></tr>
</table>

Table 34: Total launches of mission 2

There are three main contributions to the 37 total launches needed for the mission, that brings out the possible the fringes and so possible points to be improved of the biomass production system:

- The BPS needs a big amount of water but it does not produce a significant amount of oxygen. So many LGH structures have to be used, which largely increases the amount of water to be produced and then stored into the water tanks which fill 23 entire launches.
- The LGH structures are bulky and since there are 12 to carry to the Moon, the almost cover 9 launches by themselves.
- The solar panels to produce the required energy for the BPS are 820, which is a huge amount if panels. In fact they almost cover 2 entire launches even if they have divided into 9 to fill the empty spaces left by the LGH. The high energy consumption of the LGH should be reviewed.

An important remark is that the water tanks are empty. So they are very light but occupy and waste a lot of space, that could be potentially used for other payload. A possible rapid solution could me to place them as a matrioska system. It would require for example to make 4 different sizes of containers, so to be able to have 4 tanks that occupy the same volume of one. Obviously there would be less total volume, but this would be solved by adding an extra amount of tanks. Even though the number of launches would be largely reduced. The following table shows the implementation of this reduction.

Launch Type	Launcher Type	Cargo Type	Repetitions
1	Ares I	Crew	1
2	Ares V	Water	7
3	Ares V	Biomass	9
		Panels	
4	Ares V	Biomass	1
		Panels	
		Rovers	
5	Ares V	3D printer	1
		Rovers	
6	Ares V	3D printer	1
7	Ares V	WRS	1
		Microwave	
		Water	
		Rover	
TOTAL			**21**

Table 35: Optimized total launches of mission 2

Mission 3

Finally the results of the third mission option, consisting on being independent on Earth with a balanced approach in between the option 1 and 2. From SpaceNet outputs the following results have been obtained for mission option 3:

Launch Type	Launcher Type	Cargo Type	Repetitions
1	Ares I	Crew	1
2	Ares V	Water	5
3	Ares V	Biomass	1
		Rovers	
4	Ares V	Biomass	1
		Rovers	
		Oxygen	
5	Ares V	3D printer	1
		Panels	
6	Ares V	3D printer	1
7	Ares V	Oxygen	1
		Biomass	
		WRS	
8	Ares V	Rover	1
		Water	
TOTAL			**13**

Table 36: Total launches of mission 3

This option shows a more balanced distribution of the equipment. The water tanks are still a big contribution to the total launches. A similar approach to the one previously explained in option 2 could be implemented. Also the biomass equipment occupies a considerable volume. Only the BPS with its solar panels to produce the required energy could fill almost three launches. The next table shows the optimized results.

Launch Type	Launcher Type	Cargo Type	Repetitions
1	Ares I	Crew	1
2	Ares V	Water	2
3	Ares V	Biomass	1
		Rovers	
4	Ares V	Biomass	1
		Rovers	
		Oxygen	
2	Ares V	3D printer	1
		Panels	
6	Ares V	3D printer	1
7	Ares V	Oxygen	1
		Biomass	
		WRS	
8	Ares V	Rover	1
		Water	
TOTAL			**9**

Table 37: Optimized total launches of mission 3

5.2 Comparison of mission options

The next column graph shows the comparison of the total launches needed for the three mission options for the real and optimized combinations.

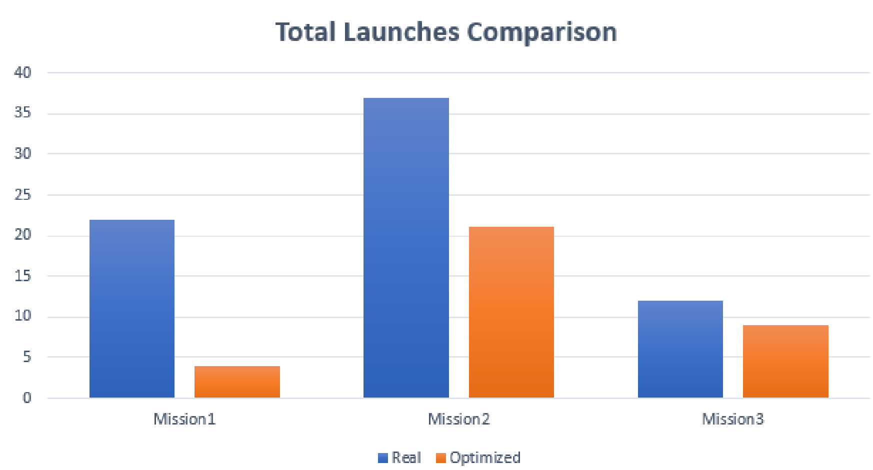


Figure 47: Comparison of launches for the 3 mission options [Own Elaboration]

The causes and effects of the optimization reductions have been already explained in the previous section. As it can be seen the biggest difference is presented for mission 1 and 2 while mission 3 shows a more balanced criterion and so a slight decrease on the number of launches.

The best way to compare the viability of our proposal is to choose the best option between the ISRU missions and then compare it with the Earth dependence option.

Clearly, option 3 largely exceeds option 2 in number of launches. The launch number is much smaller with a smaller orchard. That is the main responsible. As mentioned earlier, the BPS is the best system to produce food in-situ, but it still needs some improvements so that it can reach its maximum potential. The structure takes up a lot of space, consumes a lot of energy and needs a lot of water. All these factors mean that the LGH number has to be the minimum necessary to simply produce the necessary food. The only explanation for carrying more would be that it manages to produce the necessary oxygen and that this would be enough to counteract its disadvantages. But this is not the case. In fact two carbothermal equipment used in mission 3 are sufficient to meet the oxygen requirements, not giving options to the possibility of creating the balance of oxygen and CO2 with the garden. The graphs below verify this fact.

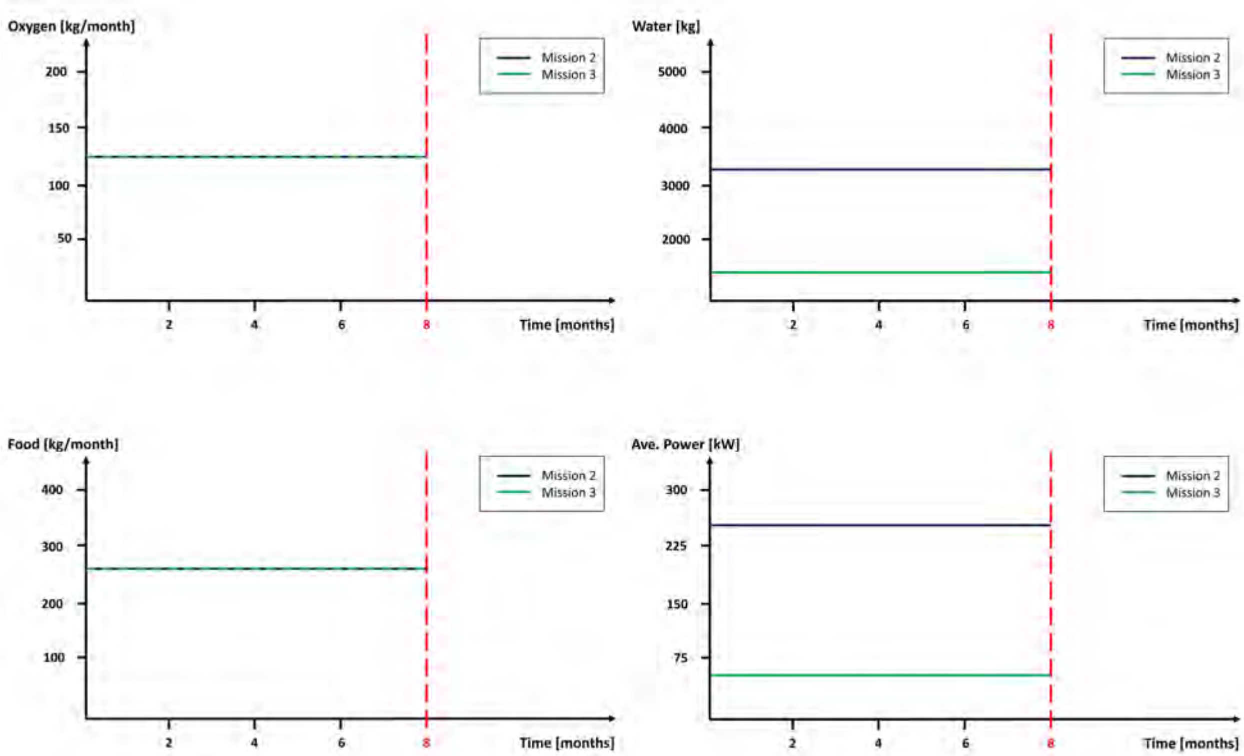


Figure 48: Mission parameters comparison between option 2 and 3 [Own Elaboration]

As the it can be observed in Figure 48 even producing the same rate of oxygen and food, mission 2 doubles its value for production of water and triples the power requirement with respect to mission

3. Therefore mission 3 is clearly a better option.

Now a direct comparison between mission 1 and 3 can be made. The launch number is less than half of that of our proposal. Therefore at first sight (following simply that graph) the technology that exists today, still would not be suitable for a space mission of that style. But the following graphs give us a second point of view. The calculated kg for each resource has been calculated in terms of amount of kg available each month.

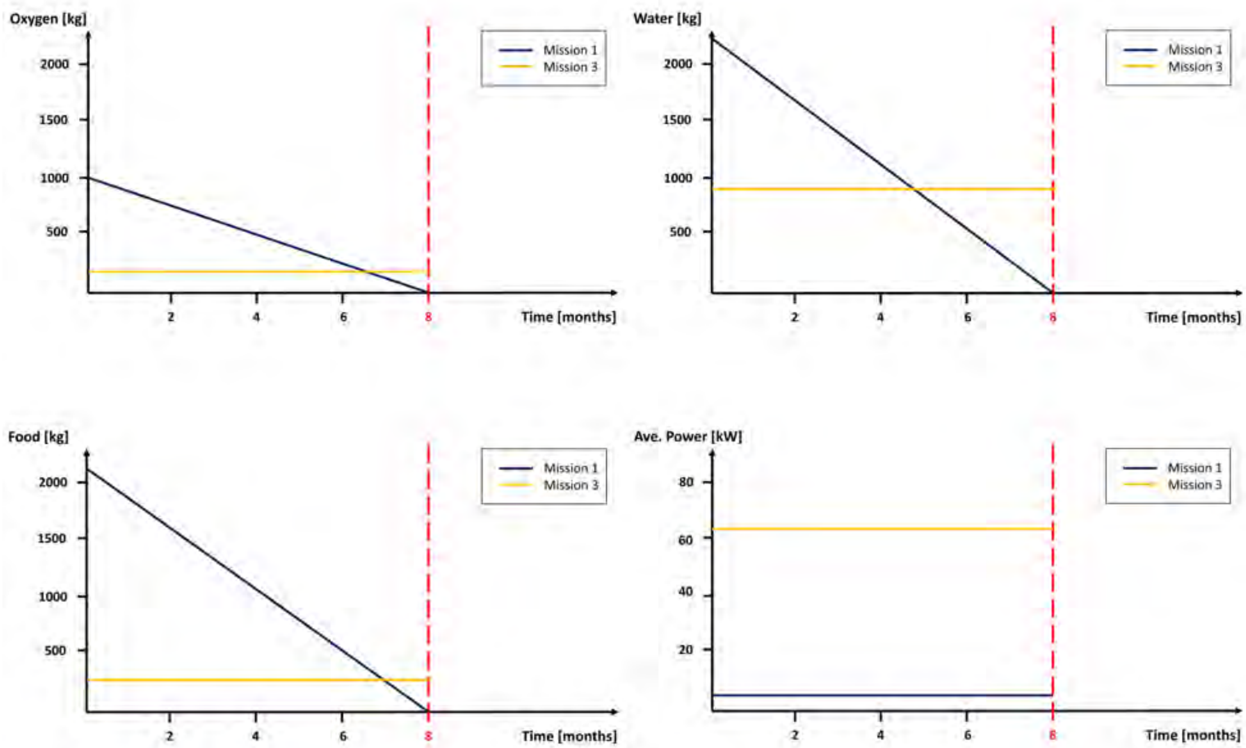


Figure 49: Mission parameters comparison between option 1 and 3 [Own Elaboration]

These images show the evolution of the production or rather the amount available each resource throughout the mission. While mission 3 demonstrates a constant production, the resources of mission 1 are decreasing linearly until they are completely exhausted at the end of the mission. This means that if the mission is extended or another mission should be done afterwards, new releases and supplies would have to be sent. On the other hand, the equipment of mission 3 would already be installed there without having to add any launch if the mission was extended. The only launch to be made for this case would be the Ares I taking the crew from Moon to Earth and vice-versa.

Therefore, the comparison can not be made simply by the number of launches, but also by having a broad and general vision of the mission. In fact, if the mission is based on considering the possible implementation of a colony and creating a base on the Moon, this proposal seems promising.

6 Conclusion

Firstly, from the obtained results it can seen that one of the three options may be completely discarded. This is the one focused on producing oxygen through the orchard equipment, LGH. The equipment that we have analyzed is not sufficiently efficient to be used for large-scale oxygen generation.

On the other hand, closely matched results can be observed between the option of bringing everything from Earth and the option of producing everything in-situ, which is differentiated from option 2 since the equipment selection is much more balanced. The results show that the first option requires approximately half of the launches of the other option. However, more insight can be gained by observing the evolution of resources over the length of the mission. With option 1 all resources are spent by the end of the mission, so that lengthening or repeating the mission inevitably requires additional launches to supply the base with the necessary resources. On the other hand, option 3 continues to generate resources beyond the target timespan, allowing for the mission to be lengthened or repeated.

Therefore, this information leads to the conclusion that two missions may be defined in terms of the intended duration. The resources carried from the Earth are exhausted after 8 months. Thus, a 16-month mission could be carried out with option 2 with the same number of launches. Therefore, the critical mission duration to differentiate between optimal approaches is 16 months.

6.1 Mission Definition

<u>Mission under 16 months</u>

In this type of mission, it is advisable to bring all resources from Earth. The mission could be defined with the necessary and chosen resources to carry it out:

- WRS would provide the necessary water for hydration and hygiene by recycling the waste produced by the crew.
- Food would be taken and divided into several packed lunches (to be consumed 3 times a day)
- 3D printer to build the shelter.
- The energy required to operate the printer would be produced by solar panels.

All this could be taken all at once or in two stages.

<u>Mission over 16 months</u>

This type of mission would be efficient for a very long duration of more than 16 months. The mission would be defined in terms of the equipment that would be carried to the Moon in order to produce the necessary resources.

- The necessary water would be produced by two different sets of equipment:
  - Food is WRS for hydration and hygiene
  - Microwave for the necessary water for the orchard

- Food is produced with the biomass production system (LGH)
- 3D printer to build the shelter.
- The oxygen would be produced by the PILOT equipment.
- Energy produced by solar panels.

The option of producing the resources on the Moon could also be used for small periodic missions. It would be based on creating a settlement on the Moon to be used as a station for humans when required. As missions to the Moon will likely be periodic, this is expected to be the most common type of mission.

Due to the advantages demonstrated by the option to create resources in-situ on the Moon, this option is the optimal approach for the near future of space exploration. For this reason, it is important to improve current technology in order to ensure the maximum possible efficiency. As has been noted in this thesis, there are several aspects that may be improved.

6.2 Solutions and improvements

As it was mentioned earlier, this mission would be the optimal for the technology that it is already tested and works today. But it could be largely improved. In fact there are many parameters that could be optimized more and thus reducing even more the number of launches and also the performance of these equipment on the Moon. By analyzing its performance it could be decided whether in some cases the technology should be only optimized and in other the whole could be re-imagined by proposing new strategies or technologies. The main elements that could be improved and that will be discussed in this section are: solar panels, shelter building, biomass production system, and the transportation tanks.

6.2.1 Solar panels

The solar panels are the only element that is carried out from Earth. There represent a huge portion of the volume occupied in the rockets since a big amount of energy would be required in such a mission.The ideal would be no to bring the panels from Earth but already have it there. But how could be achieved that?

There exists a possibility to create solar panels on the Moon using a specific robot, which is shown in the Figure below.

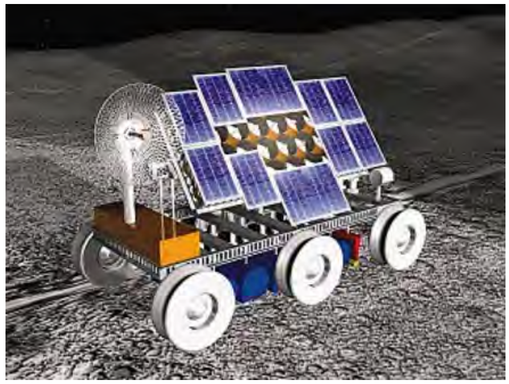


Figure 50: Solar Panel Schematic in a lunar environment [41]

It is still a theoretical idea, and it has not been tested nor tried yet. It consists of a rover that would be able to build solar panel in-situ using the lunar material. In fact the main material to build such a panel would be silicon which is the one that can be found in the moon surface. However with that material, the panels would not be as efficient as the would be. But that could be compensated by building many solar cells [41]. TO understand better how it would work the process is now presented [41]:

- The development of each solar cell would begin with the identification of the lunar rocks with the highest concentration of silicon.
- Then the robotic ship would use its own solar panels to generate a power of 60 watts per square centimeter and direct it to those rocks.
- Thanks to the energy used to "melt" the rocks in the lunar soil, a layer of a material that is very similar to traditional glass will be formed. This plate will be about 0.4 centimeters thick and, by its characteristics, it will be able to absorb the energy of the Sun and also to accumulate it, like the traditional solar panels that we know on Earth.
- Scientists calculate that each lunar solar panel will have a rectangular shape. These will be placed directly on the lunar surface.
- The solar cells would be built one by one. These will be placed continuously, creating a row of solar panels that will look like a kind of metal tape attached to the surface of the Moon.
- It is estimated that the first line of solar cells that are manufactured could measure about one meter wide by two meters long. These would weigh about 300 kilograms and their production could take at least two hours.
- For each meter of length, the solar cells would be able to generate about 100 megawatts or even one gigawatt.

This idea seems very promising and it could be the next step for the power generation in the near future.

6.2.2 Shelter building

It has been proved that the main technology to be used for building the shelters is 3D printing. The only one that seems to be ready right now is the D-shape. But as it was seen through the analysis it may present several problems:

- Its volume is too high and it increases the number of launches.
- Its set up is no easy. It would required a large amount of rovers with difficult application.
- The printing time could take a long time.

The D-shape uses the technique of printing of 1 to 1 scale, and this is what makes the disadvantages previously enumerated to appear. So maybe a good idea would be to think outside the box and see new strategies or approaches that could solve those problems and not lose performance. There already some thoughts and ideas that could contribute to this matters: the inflatable shelter units and the lava tubes.

<u>Inflatable habitation</u>

An alternative option would be the inflatable habitation. This is considered in different future lunar projects such as Moon Village, but it is not ready yet. These inflatable units are basically a flexible pressure vessel that could be folded compactly when shipped into the launchers but fully deployed on delivery [51]. The next Figure shows the sketch of the main idea for this particular lunar habitat:

Figure 51: Inflatable habitats idealization proposed in Moon Village Project [Google]

These kinds of structures show great potential opportunities because they would be able to provide a safe and adequate environment while minimizing the volume for transportation. The main advantages that an inflatable habitation could provide are now enumerated:

- As it was mentioned before, the cost of each launch is very expensive, so an important requirement is to use each m^3 of the volume capacity as efficient as possible. This method allows this volume reduction when shipped as payload into the rocket.
- The habitation dimensions would also be bigger than the one that d-shape could provide more space to accept the operations of bulky equipment.

- It also provides better habitability. The larger space and the better conditions would provide a more pleasant place, which is an important factor for the astronauts if they are going to be there for long-term missions. This would also make it a more productive place to work in.

The methodology to build these structures would involve 3D printing technology. In fact in order to protect the inflatable unit from radiation and the harsh lunar environment, a layer of regolith should cover the entire habitation. To make it consistent a 3D printer placed on a rover should melt this regolith so to then it to cold and produce a solid mixture that would fulfill the protection requirements. This alternative seems very promising but for now it presents some issues that may be solved. These problems consist on the resistance of the units to the lunar environment. The proper material should be found to resist to factors such as temperature sensitivity and radiation resistance. Even though, it should be the technology to be developed for a near future long-term mission in the Moon.

Lava Tubes

Another alternative that is worth mentioning for its different approach in the solution is the lava tubes. When the moon was forming and there was the impact with the Earth, a basaltic flow stand was created that covered the surface of the moon, taking the name of Lava Sea. After that the lava gradually solidified. This caused vacuum tubes to be created below the surface. There are areas where there are gaps due to the collapse of the lava. We could be talking about holes up to 60 meters deep and 90 of diameter [52]. In these areas the appearance is quite similar to that of a cave because it is a shadowed area, but with much more depth. Therefore it could be an alternative as the habitation place for a moon-based mission.

Among the advantages we find that the crew would have a natural protection to the difficult conditions of the moon. However we would not be taking advantage of sunlight, which is one of the main resources to drive the machinery.

It is also an alternative that is worth continuing to be investigated and analyzed because it could have quite potential. As it continues in its early stages of validation and idealization its possible implementation could appear in the distant future.

6.2.3 Biomass system

It can be stated that the biomass system is the one that contribute the most on volume, mass and so on number of launches. The main issue is that in order to have a closed loop system, large capsules have to be made to ensure the correct environment and lightness. This structure is usually very large and high power and water consuming. Some other options could be explored analyzing each individual problem inside the biomass system:

- Lightning: Having artificial lights consumes a lot of energy. Being on the South Pole where there is almost permanent sunlight, it could be used by having some natural light getting into the orchard by setting transparent shelters or some windows.
- Water supply: The water quantity required by the system is very high. This compromise the mission since a big amount of water should be produced. Creating a special irrigation system

where the water could be reused could significantly reduce the water production.

- Structure: The LGH consists on a intruding structure. As it was proved in the simulation, the biomass capsules occupies a big amount of space on each launch. Reducing it could largely improve the launch number. An option could be try not to bring any structure but adapt a shelter to the biomass process and environment.

On the other hand, it is also worth mentioning that it is not only about the structural and performance issues but also about the output. The variety of crops that can be grown is still very limited and it would directly affect to the crew and its diet. In fact, having more variety could have a direct positive effect on the crew, psychologically speaking.

6.2.4 Water tanks

The water tanks volume problems have been the tonic of the whole simulations for each missions. The importance of water in the mission but the difficulties to store it since its volume, makes it a real challenge to try to fix this problem.

The main issue is the container's volume, which is empty, so it is a waste of space. The "matrioska" option could be useful as a temporal option but not the definitive one. The most innovative option would be to create some inflatable tanks, which would have in the Moon the required volume but when launched they would occupy very little.

This seems promising. In order for it to succeed several aspects should be taken into account such as the materials to be used in order for the container to resist the harsh lunar environment.

6.3 Future repercussion

Applying these improvements to make this mission possible would have a great impact in the future. Being able to have a fixed base on the Moon would greatly facilitate direct research on our satellite, accelerating the process of knowledge of the lunar surface and its characteristics and also leading to new discoveries. It would also suppose a test bed and a station for the next big step that is already being considered, which is to create a settlement on Mars and thus be able to continue advancing more and more in space exploration.

The implementation and study of this mission will not only have repercussions in the space sector. It will also greatly influence social life. The research in the technology can carry out all of this will also lead to new discoveries or technological improvements that will affect our daily life.

Also, it could approach regular people to space. In fact, there are some companies that are already thinking about it. An example would be the American company Space X, that has admitted in several occasions that the possible date for the first commercial trip for two people to Mars making a turn around the Moon to take place could be in 2019. But for this trip it would not be possible to access to the lunar surface, which the last time this happened was in 1969. In fact, since then no astronaut has gone back to the Moon. But with these new developments it is not discarded that tourist trips could be on the lunar surface.

If in the future these lunar colonies are carried out, the tourist trips to the Moon could be guaranteed by the strong economic investments coming from the private sector that would find a great business opportunity. That would have as consequence a considerable boost to science, to technology, to engineering and more generally in the economy, with important social repercussions, such as the growth of the employment rate of qualified professionals.

Due investment reductions levels from Russia and the United States, advances in the field of manned space exploration have been slower than it could be assumed in the middle of the last century. Hopefully this trend can be reversed through the support between private initiative and the State.

It is for all these reasons and future repercussions that it is worthwhile to continue investigating and innovating in new strategies and technologies that allow us to facilitate space exploration.

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A Socio-Economic Environment

A.1 Project Budget

In order to carry out this thesis, no particular financing has been needed to obtain the required results. The cost to make the thesis only takes into account the equipment and resources used.

- Primarily this has been a research work where several documents have been necessary to collect all the information necessary to carry out the analysis of this work. Many of the documents are available on the Internet others belong some private websites and therefore a small investment to access them is necessary.
- To get the results and simulations, the BioSim and SpaceNet programs have been used. Any type of license has been required to access them since it is accessible to everyone on the Internet.
- The computer equipment I used for the project is an HP Envy computer that costs around 900€.
- Also a small investment in printing copies of some information documents or user manual has been made.

If a company wanted to do a research work of the same style, the same costs would be considered but it would be added the price to have a newly graduated engineer and also a tutor supervising the work.

- A cost that could be considered is the supervision of the tutor throughout the work. Considering that it could cost as a private class (15 €/h). Considering 2h per week for three months, the cost would be 360 €.
- In addition to having an intern engineer doing this work that has an estimated dedication of 300 €, and that as much can earn 9 €/h. The cost would be 2700 €.

The following table shows the budget summary required to do this thesis or the same research in a professional field.

	PC	**Author**	**Supervisor**	**Articles**	**Printing**	**Programs**	**TOTAL**
Thesis	900 €	0 €	0 €	50 €	20 €	0 €	**970 €**
Professional	900 €	2700 €	360 €	50 €	20 €	0 €	**4030 €**

Table 38: Project budget

A.2 Socio-Economic Impact

The analysis and conclusion obtained in this thesis are a positive contribution in the study of ISRU technology. Even if this thesis alone will not have any significant socio-economic impact, the eventual real application of what has been discussed in the Research could have a considerable effect in the space exploration sector. The main repercussions that the technology development would have in social or economic terms are:

- Space travel would be more efficient and cheaper in long-term purposes. This would enhance space exploration and it would take more and more importance over the years.
- The main results of this space exploration would be the new discoveries that it would bring. These discoveries will convince and encourage the countries for more investments in the subject. In other words it could change the society's view about the space exploration.
- Investigating and innovating in new hight technology would also have a direct impact in the society. It would take new technology that could be used in our daily life making our life easier.
- Having a moon-base in the Moon or in Mars would open new frontiers and new possible ways of thinking. It would help to broaden our horizons.

The main problem that holds back these explorations is financing. These missions require a large money investment, which really few governments are willing to prioritize during these years of economic crisis. In the future it seems more and more possible that the private sector will provide this kind of funding.

Despite the difficulties, there are companies that are focused on this kind of research and are willing to make possible these new space missions and keep evolving. The most notorious examples are NASA and ESA. But as we have seen during the investigation there are many more that continue to investigate and deepen in it as Regolight, CORBITEC, CC Corp, etc.

B Regulatory Framework

The 10^{th} October 1967 entered into force the Outer Space Treaty, which is a treaty that forms the basis of international space law. It is basically the legislation that collects the principles governing the activities of states in the exploration and use of outer space, including the Moon and all the celestial bodies. Nowadays 107 countries are part of this treaty, including Spain.

It is used to ensure that space is being used with peace purposes without creating possible rivalries between countries focused on the conquest of space. In fact this treaty declares outer space a home for humanity. It means that the space exploration must be beneficial to all countries. there does not have to be discriminations and the access to the planets and celestial bodies must be free. Any nation can appropriate of outer space. Therefore there must not be any military purposes.

Therefore the possibility of creating a base in the Moon and all the elements discussed in this thesis would be allowed since its objectives are fully scientific.